INTEGRAL Science Data Centre

SPI Analysis User Manual

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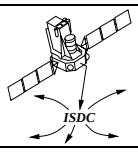 ISDC	SPI Analysis User Manual	
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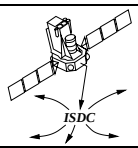 ISDC	SPI Analysis User Manual
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Acronyms and Abbreviations

AD	Architectural Design
ADD	Architectural Design Document
ACS	Anti-Coincidence Shield
ARF	Ancillary Response Files
BGO	Bismuth Germanate
DFEE	Digital Front End Electronics
DOL	Data Object Locator
DPE	Data Processing Electronics
DS	Data Structure
FCFOV	Fully Coded Field of View
FOV	Field of View
FWHM	Full Width at Half Maximum
GRB	Gamma Ray Burst
GTI	Good Time Interval
IC	Instrument Characteristics
IRF	Image Responce File
ISDC	Integral Science Data Center
OBT	On-Board Time
OG	Observation Group
PHA	Pulse Height Amplifier
PI	Pulse Invariant
PSA	Pulse Shape Amplifier
PSAC	Plastic Scintillator Anti Coincidence Subassembly
PSD	Pulse Shape Discriminator System
RMF	Redistribution Matrix Files
ScW	Science Window
SWG	Science Window Group
TBW	To be written
TM	Telemetry
UTC	Coordinated Universal Time

Part I

Instrument Definition

1 Scientific Performances Summary

The spectrometer SPI (SPectrometer on INTEGRAL) performs spectral analysis of gamma-ray point sources and extended regions in the 20 keV - 8 MeV energy range. The main characteristics of the instrument are given in Table 1.

Table 1: Main characteristics of the SPI instrument.

Mask dimensions	665 mm flat to flat 30 mm thick Tungsten
Detector unit	Encapsulated Ge, hexagonal geometry, 19 detectors 70 mm thick
Energy range	20 keV - 8 MeV
Energy resolution (FWHM)	2.2 keV at 1.33 MeV for each detector, 3 keV for the whole spectrometer.
Angular resolution	2.5° for point sources.
Point source positioning	<1.3° for point sources (depending on point source intensity).
Field-of-View fully coded:	13.2° flat to flat (fully coded), 16° corner to corner zero coding: 30.5° flat to flat, 35° corner to corner (zero sensitivity)

2 Instrument Description

2.1 The Overall Design

The SPI instrument design is based on a hexagonal geometry, which is the most compact one. The instrument is a coded mask spectrometer. An overall cut-out view of the instrument is given in Figure 1.

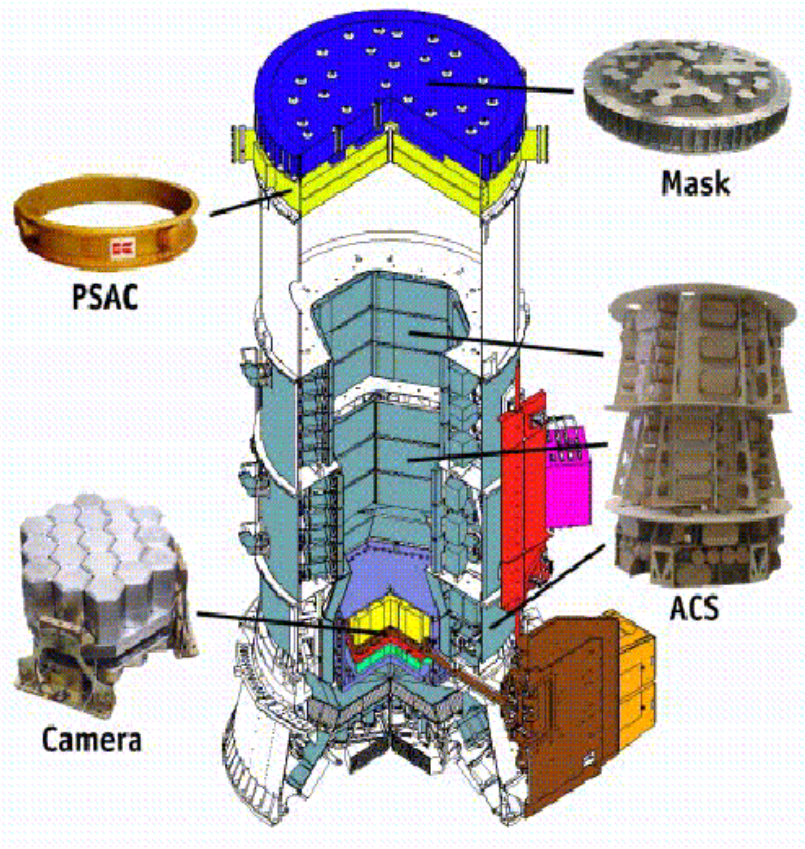


Figure 1: A cut-away view of the SPI instrument. The mask, plastic scintillator, camera and ACS subsystems are highlighted.

The detector of the instrument consists of 19 cooled, hexagonally shaped, high purity Ge detectors, providing a total area of about 500 cm^2. The background on the detectors is limited by the use of several methods. A Pulse Shape Discriminator system (PSD) reduces the β decay background in the Ge. An Anti-Coincidence Shield (ACS), consisting of 91 bismuth-germanium (BGO) scintillator blocks vetos out-of-field photons and particles, and a plastic scintillator (PSAC) underneath the coded mask vetos charged particles. The veto shield also defines the field-of-view of the instrument, since it vetoes the out-of-field photons. The sensitivity of the instrument is limited by the background due to the primary and secondary cosmic ray particles and the cosmic background radiation.

2.2 The Passive Mask

The passive mask is located at the top of the SPI instrument, above the plastic scintillator. The purpose of the mask is to code the incident gamma rays in the field-of-view, giving the instrument imaging capabilities. The mask also provides stiffness to the primary structure of the SPI instrument. The mask consists of a sandwich structure made of:

- a honeycomb core covered by two skins,
- a titanium ring that forms the interface to the rest of the instrument
- a coded motif made of hexagonal tungsten blocks that are stuck and screwed onto the sandwich structure. Motif is symmetric for 120°rotation

The tungsten motif provides the specific transparency and geometry for the mask. The mask is made of 127 elements of hexagonal shape and inscribed in a 78 cm diameter circle. Of these elements 63 are opaque and 64 are transparent. Each opaque element is 30 mm thick and 60 mm flat to flat in size. The tungsten elements stop the gamma ray radiation in the range 20 keV to 8 MeV with an absorption efficiency greater than 95% at 1 MeV. The holes in the mask have a gamma ray transparency of 60% at 20 keV and 80% at 50 keV. The mask is located 171 cm from the detector plane. The distance between the mask and the detector plane is driven by the required field-of-view and angular resolution. A picture of the mask pattern is given in Figure 2.

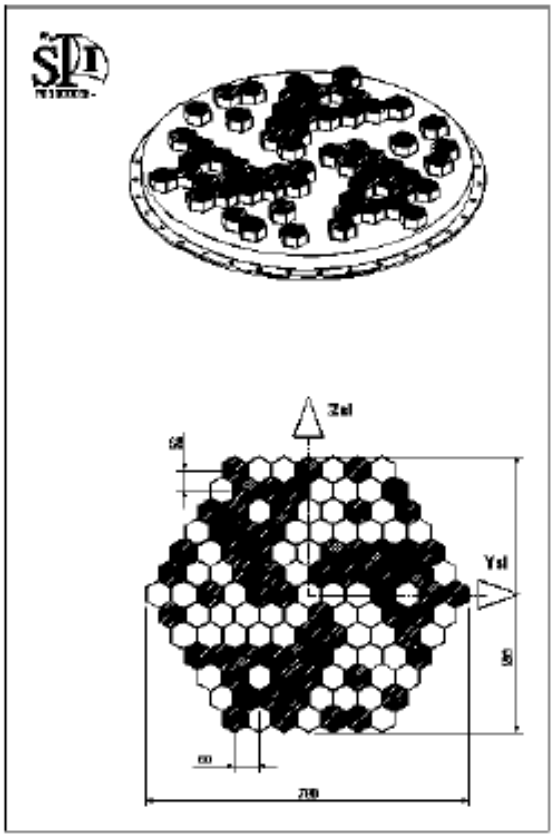


Figure 2: The passive mask of the SPI instrument. The bottom picture indicates the direction of the spacecraft Y and Z axes with respect to the mask.

2.3 The Camera

2.3.1 Cryostat

For an optimum sensitivity and resolution the detectors of the SPI instrument have to be kept at a constant, low temperature of 85 K. The SPI cryostat (which is made in Be) is designed to keep the detectors at this optimum operating temperature. The cryostat is composed of three parts: an active cooling system, a passive cooling system and a cold box. The active cooling system brings

the temperature of the cold plate on which the detectors are mounted down to 85 K, using two pairs of cryocoolers. In normal operating mode all coolers work simultaneously. In case of failure of one of the cryocoolers, or of the electronics, the instrument will be functional, but in a degraded mode, as the detector temperature can rise to more than 100 K. The detector assembly is placed inside the cold box, which is kept at approximately 210 K by the passive cooling system. All temperatures of the cryostat subsystems are regularly monitored to provide the ground operators with early warnings on failures of coolers, and to provide temperature information that can be used for the data processing.

2.3.2 Detectors and Pre-Amplifiers

The detectors used for SPI are 19 hexagonal-shaped Be encapsulated high purity Germanium detectors, mounted on a cold plate at 85 K, as close as possible together. The size of the detectors is 5.6 cm, flat to flat, with a height of 7 cm. The cold plate is made of beryllium and it is directly cooled by the SPI cooling system. The bottom of the cold plate is hollowed to mount the printed board pre-amplifiers (PA-1) cold electronics. The PA-1 electronics include the high voltage filter and the connection between the detector and the Charge Sensitive Amplifier (CSA). A second set of 19 pre-amplifiers (PA-2) is mounted on a second cold plate (beryllium, at 210 K). The PA-2 is connected to the PA-1 with a cryogenic cable.

The hexagonal detectors are mounted with minimum space between them, such that the axes of two adjacent detectors are 6 cm apart. The material in front of the detector has good transparency for gamma-rays at 20 keV. To cure the degeneration of the Ge detectors, an annealing operation should be done every 6 to 12 months, strongly dependent on the high energy neutron flux at the satellite position, in which the detectors are heated to 105 degrees C. The instrument will not be available for scientific observations during the time needed for the annealing operation and the cooling phase afterwards (in total approximately 200 hours).

2.3.3 The Detector Electronics

The signals from the pre-amplifiers are sent to the amplification chain, which is made up of a Pulse Shape Amplifier (PSA) and a Pulse Height Amplifier (PHA). The PSA amplifies the pulses such that the performance of the spectrometer is optimized. This is done by making a compromise between getting the best signal to noise ratio for the pulses, operating in the full 20 keV-8 MeV energy band of the instrument without resolution degradation, and making the output pulses insensitive to the fluctuations in the detector signal rise time. The PHA is used to maintain the energy resolution in the full 20 keV-2 MeV or 2 MeV to 8 MeV range. Finally the detector electronics also comprise a high voltage power supply (0-5000 V) and a low voltage power supply (19 independent chains per amplification chain).

2.3.4 Pulse Shape Discriminator (PSD)

The PSD subsystem compares the form of the pulses produced by the pre-amplifiers with profiles stored in an on-board archive. Based on this comparison the PSD flags each event with a signal type (single or multiple event), and consequently the type of processing necessary. Only non-vetoed events are processed by the PSD. The output of the PSD is provided to the Data Processing Electronics (DPE, see below). The PSD works in an energy range from 200 keV to 1 MeV. The on-board pulse shape library will be updated twice a year in connection with the annealing of the detectors. The PSD is important to identify the background photons impacting on the detector. It can reduce the background between 200 keV and 1 MeV, and thus increases the sensitivity of the instrument in this energy range.

2.4 Anti-Coincidence Subassembly (ACS)

The main function of the Anti-Coincidence Subassembly (ACS) is to shield the Ge detectors against background (photons and particles) from sources outside the field-of-view. The ACS system consists of 91 Bismuth Germanate (BGO) scintillator crystals in combination with photo multiplier tubes. The BGO crystal thickness has been optimized with Monte Carlo simulations to minimize the detector background (by minimizing the shield leakage and neutron induced radiation in the BGO). The BGO shield for the side and the rear of the camera is 5 cm thick. The complete shield consists of two collimator rings (that define the SPI field-of-view), located between the mask and the camera unit, a side shield and a rear shield that surround the camera. The BGO scintillator crystals are used to convert all incoming events into photons in the 480 nm region (visible light). Photo-multiplier tubes are used to detect these photons and convert them into electrical pulses which are sorted, normalized and summed up by the ACS electronics. Each photon induces a time tagged veto signal. The ACS output data is directed to the Digital Front End Electronics (DFEE) which formats the data and time tags each event. Photons that are not in coincidence with an ACS veto event are considered good. The ACS-off photons (i.e all photons that are detected by the Ge detectors, independent of the veto status) are integrated into background spectra, that are sent to the ground every 30 minutes.

2.5 The Plastic Scintillator Anti Coincidence Subassembly (PSAC)

The purpose of the plastic scintillator subassembly (PSAC) is to reduce the 511 keV background due to particle emission by the passive mask. The detector consists of a plastic scintillator inside a light tight box, located just below the passive mask. It has a good gamma ray transparency, and actively detects particles which deposit energies in excess of 300 keV. The light flashes that are produced by the impacts of these high energy particles are detected with four photo multiplier tubes located around the light-tight box and converted into electrical pulses which are processed by the PSAC electronics assembly. The electronics send a veto signal associated with the detected events and compatible with the Anti-Coincidence Subassembly (ACS) Front End electronics veto signal to the veto control unit of the ACS.

2.6 Electronics

The electronics is divided into the Digital Front End Electronics (DFEE) and the Data Processing Electronics (DPE). The DFEE is in charge of the real time acquisition, assembly, time stamping and intermediate storage of the various pieces of information coming from the SPI front end systems (detector electronics, PSD, ACS etc.). The DFEE will subdivide the events into classes depending on their origin in the instrument (detector electronics, Ge detectors, PSD, veto shield) and will handle overall event energies and system monitoring statistics (dead time, signal counts etc.). The detected events are time tagged with a 20 MHz local clock, which provides the timing resolution. The reset (timing reference) is done with the 8 Hz satellite clock. The DFEE uses the 125 ms time frames to analyze and process the input information and pass it on to the DPE. The statistics are passed on to the DPE every second. The DPE is the interface to the instrument. It is part of the On-Board Data Handling (OBDH) unit. It provides the telecommand and telemetry interfaces to the instrument and it provides the environment for the instrument dedicated software (Instrument Application Software, IASW).

3 Instrument Operations

3.1 How the instrument works

The SPI instrument provides a combination of high-resolution spectroscopy with imaging capabilities. The performance characteristics of the instrument each depend on one of the instrumental subsystems:

- Energy resolution: is determined by the cooled Ge detectors
- Angular resolution: is determined by the pixel size of the mask and the detector and the distance between them. However imaging with SPI requires a special operation (dither) since a single pointing does not unambiguously define a sky image. For this the 5 by 5 and hexagonal dithers have to be used (see below).
- Field-of-View: determined by the area of the mask and the detector and the distance between them, as well as the ACS shield.
- Sensitivity: achieved by making the detector as large as possible and by minimizing the background (by using an ACS that is optimized in material and thickness, by incorporating a PSD system, by carefully choosing the materials used in the instrument and by adding a plastic scintillator below the mask).

The passive mask provides the shadowgram for image reconstruction. The PSAC detects energetic particles originating in the mask, and provokes a veto pulse from the veto system. The ACS detects gamma rays and charged particles from out of field sources, and also provokes a veto pulse. Each photon that is absorbed in a Ge detector will give a pulse that is sent to the electronics. The electronics analyses the incoming pulses and the veto signals and tags each photon with the energy, the time and the type of event (i.e. single detector events with or without PSD and multiple detector events). These data are then sent to the ground (see below). The ACS-off photons are summed into background spectra, that are sent to the ground every 30 minutes.

3.2 Operating Modes

The SPI instrument has only one mode for normal observations. All scientific observations with SPI are done in so called photon by photon mode with a high temporal resolution. In this mode scientific data is collected and transmitted to the ground for each photon. For each detected photon, date is sent to the ground from which the type of event, the energy and the timing can be deduced. Furthermore detector spectra of all events (including vetoed events) are accumulated and transmitted every 30 minutes. In case the SPI telemetry is continuously overflowing due to background radiation that is higher than expected or due to a strong solar flare, the instrument can be operated in a degraded science mode (TM emergency mode). In this case the on-board processing and transmission of data will be restricted to good events (non-vetoed), ACS-off energy spectra, and PSD events. The maximum data generation rate in this mode will be about half the rate for normal photon by photon mode. The observer cannot select the TM emergency mode, it is commanded by the ground controllers in case of need.

Before any change of mode the SPI instrument will be put into a special configuration mode. This is the only mode in which changes to the instruments configuration can be made. The instrument will not be taking scientific data when in configuration mode (science telemetry processing is stopped). Several other special modes are available for early in the mission, for engineering tasks (e.g. annealing) and for instrument calibrations (e.g. PSD calibration).

3.3 Dead Time

Due to several causes (e.g. veto signals), the SPI instrument experiences within a normal exposure, a dead time, during which no useful scientific data are collected. Simulations and tests have shown that this dead time is about 12% of the observing time. However, it depends on several external conditions (e.g. increase of the ACS rate during a solar flare), and thus will only be known accurately after launch. This takes also into account the dead time as a result of ACS vetoes (BGO and plastic scintillator).

3.4 Telemetry Budget

The allocation of telemetry to the SPI instrument in photon by photon or TM emergency mode is 16 kilobits per second (kbps) in solar maximum and 20 kbps in solar minimum. INTEGRAL uses packet telemetry. Each packet corresponds to 0.44 kbps, so the above allocations translate into 36 and 46 packets for solar maximum and solar minimum cases respectively. The model calculations, done by the University of Southampton (England) using the INTEGRAL Mass Model and by the SPI instrument team, show that in solar maximum a rate of 8 events/s/det is to be expected (although it might reach 12 events/s/det especially taking into account the contributions of background lines), whereas in solar minimum this goes up to 20 events/s/det. These events are split into 45.6% singles (event detected by only one detector and not processed with a PSD), 42.3% PSD events (event detected by only one detector and processed with a PSD) and 12.1% multiple events (events, detected by more then one detector). The total telemetry rate then will be 17 packets per cycle in solar maximum (7.5 kbps) and 41 packets per cycle in solar minimum (18 kbps). In addition to the telemetry needed for the photon-by-photon data, every 30 minutes the ACS-off spectra are transmitted. This nominally requires 5 packets per cycle (1.9 kbps). The total nominal SPI telemetry thus is 22 packets per cycle for solar maximum (10 kbps) and 46 packets per cycle in solar minimum (20 kbps). If needed, the amount of telemetry in solar minimum can be reduced by increasing the low-energy threshold to 100 keV, but this is at the cost of loss of some science. Changing the low-energy threshold cannot be done by the observer, but is done by the INTEGRAL ground segment if deemed necessary.

4 Using the Instrument

4.1 Spectroscopy & Timing

In the standard observing mode the instrument can be used for spectroscopy and timing observations. Since every photon is tagged with an accurate time, these data can also be used for timing analysis.

It is expected that the background in each of the 19 independent detectors will vary in time in a different way. This variation can limit the sensitivity that is obtainable. Several types of background variations can be anticipated:

- short-term variations due to solar activity and solar system weather.
- variations over the orbital period (related to the position of INTEGRAL in the orbit).
- long-term variations over the mission duration.

In order to reconstruct the image on the detectors for all pixels in the field-of-view (25 degree field, with 2 degree resolution) for a single pointing a set of 19 equations with 156 unknowns would need to be solved. This is impossible, and the only way to increase the number of equations and make the system solvable is to observe more pointings. Thus, in order to solve this problem of background determination an appropriate dithering strategy has to be adopted for every observation. Dithering is also important to improve the image quality of reconstructed sky images. The dithering strategy that has to be adopted depends on the circumstances:

- observations of a single point source of known location, where there are no known other objects of significant intensity in the field-of-view (fully and partially coded, for all dithering points, i.e. within a radius of about 20°). In this case the hexagonal dithering pattern can be used, where a hexagonal scan is performed with one pointing centered on the source, surrounded by six pointings with distances of 2°. Note that the number of sources for which this dithering pattern can be used is very limited.
- observations of a region of multiple or complex sources or of sources with poorly known position. In this case the 5 by 5 rectangular dithering pattern should be used, where 25 points on a rectangular grid with 2°spacing around the source position are observed.

Both dithering patterns use a dwell time of 30 minutes per point. This is optimized for the instrument performance and expected background variations.

All SPI observations should use dithering, since reconstruction for pointed observations is very difficult, if not impossible, due to background inhomogeneity over the detector plane.

4.2 Imaging

The imaging performance of SPI depends also on the dithering pattern that is used. In general the greater the number of pointings, the better the imaging. Calculations were done to estimate the imaging performance of the instrument using simple correlation mapping. More sophisticated techniques may be used to reduce or remove artifacts present in such images, but this can only be done at the expense of worsening the signal to noise ratio or worsening correlations between parts of the image. In these calculations the background in each detector at each energy is assumed to be constant, but different between detectors. The calculations show that, when using the hexagonal dither pattern the reconstructed point source response function shows very strong side lobes at distances of 10°to 20°from the center. Therefore this mode should only be used for isolated point sources and is not really suitable for imaging. The side lobes are still present, but significantly less

with the 5 by 5 dither pattern (about 50% of the hexagonal case). To remove these side lobes, which will cause artifacts in reconstructed images, the only possibility is to enlarge the imaged area by observing multiple pointings (i.e. multiple dither patterns).

4.3 Gamma-ray Burst Detection

The ACS system of SPI will detect gamma ray photons from a large part of the sky during all observations. It can thus function as a gamma ray burst monitor. Because of the size of the ACS BGO shield it has a high sensitivity for gamma ray bursts. A sensitivity calculation shows that SPI will detect of the order of a few hundred gamma ray bursts per year (minimal detectable energy flux between 4×10^{-7} erg cm^{-2} s^{-1} and 7×10^{-7} erg cm^{-2}s^{-1}). This is comparable to BATSE.

Unfortunately the ACS data cannot be directionally sensitive, therefore accurate positions of gamma ray bursts that are detected with the ACS have to be determined through triangulation methods, with other (distant) spacecraft (e.g. Ulysses). To accommodate these triangulations, the acquisition of the veto count which is done every 50 ms, has a timing error of about 2.5 ms.

The INTEGRAL Science Data Centre (ISDC) will check the stream of veto count rates automatically. If a gamma ray burst is detected (sudden increase in the count rate over a short period of time), an alert will be issued to the institutes that are doing the triangulation observations (4th Interplanetary Network). From the accurate timings of the SPI detection and detections by other spacecraft a position will be constructed that is communicated to the world. The accuracy that can be achieved with this method is much better than an arcminute (due to the long baseline, and the accurate timing of the SPI ACS events). Note that the ACS events are written to the instrument House Keeping and are therefore made public immediately.

Observers can be notified of these gamma ray burst events by subscribing to the gamma ray burst alert system of the INTEGRAL Science Data Centre. GRBs can of course also be detected in the field-of-view of SPI using the normal photon-by-photon mode. In this case the data belongs to the observer who has a accepted proposal for GRBs in the field-of-view.

5 Performance of the Instrument

5.1 Components and Sources of Instrumental Background

The SPI instrument is background limited. The sensitivity of the instrument is therefore largely dependent on the background and on the correct identification of background photons. The background can be divided into the following main components:

- continuum radiation
- 511 keV line radiation
- gamma ray lines

5.1.1 Continuum Background

The continuum background can be split into several components, depending on their origin. First the radiation coming from outside the instrument. This can be the cosmic diffuse gamma ray flux that comes in through the instrument aperture, or leakage through the BGO shield of cosmic diffuse gamma ray radiation and gamma continuum radiation from the spacecraft (induces by energetic cosmic ray particles). Secondly scattering in the Ge detectors of neutrons that were produced in the spacecraft or other parts of the instrument. Thirdly background components produced inside the spectrometer detectors. These consist of localized β^- decays, non localized β^- decays and β^+decays. About 90% of localized β^- decays (single events) are identified by the pulse shape discriminator system. The non-localized β^- decays (multiple interactions in the detector, e.g. Compton scattering and photoelectric interaction) are more difficult to identify, since in this case the electron and the gamma photon are emitted simultaneously, therefore the resulting pulse looks like a normal source event for the PSD. The continuum emission from the mask and the BGO emission when the veto electronics are blacked out (veto dead time) are negligible. The individual components and the total continuum background emission are illustrated in Figure 3.

5.1.2 511 keV Background

The 511 keV background can be split into five components:

- the continuum background under the 511 keV line. This component is estimated from the continuum background spectrum as explained above.
- passive material: 511 keV photons from passive material, due to β^+ decays of unstable nuclei in these materials. These unstable nuclei are formed due to interactions of protons and neutrons that are produced in interactions of cosmic ray particles with the detectors, shield or cryostat. The unstable nuclei decay through β^+ decay. The annihilation of the positron leads to the emission of two 511 keV photons in opposite directions. If one is absorbed by the detector and the other escapes, a 511 keV background event is produced.
- shield leakage: 511 keV photons, originating from interactions of cosmic rays with passive spacecraft materials, that are not rejected by the BGO shield.
- mask component: 511 keV photons originating from cosmic ray interactions with the mask material. The main source is pair creation by cosmic ray proton interactions with W nuclei. This component can be reduced significantly with the Plastic Scintillator.
- BGO shield blocking time component: 511 keV photons produced by β^+ decays in the BGO shield when the ACS electronics is blocked by a large energy deposit and the veto is on.

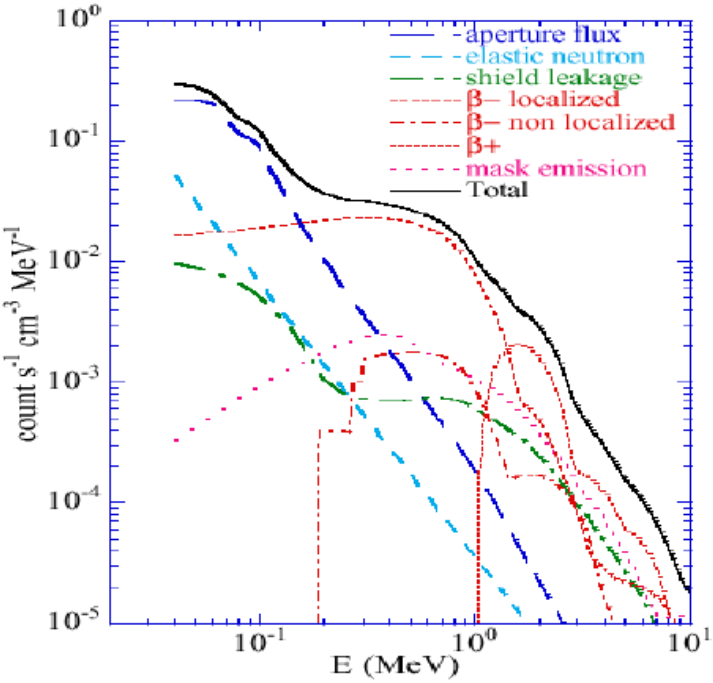


Figure 3: The continuum background components for SPI. The individual components are identified. The total background spectrum is indicated with the black line.

All these components were calculated with a Monte Carlo method. The resulting line strengths for the 511 keV line with and without the PSAC are given in Table 2.

component	with PSAC	without PSAC
continuum	4.9×10^{-5}	5.4×10^{-5}
passive material	2.5×10^{-4}	2.5×10^{-4}
shield leakage	8.6×10^{-6}	8.6×10^{-6}
mask	1.2×10^{-5}	2.1×10^{-4}
BGO shield blocking time	1.4×10^{-6}	1.4×10^{-6}
Total	3.2×10^{-4}	5.2×10^{-4}

Table 2: 511 keV background line strength with and without PSAC. Calculations are for 5 cm BGO shield, 80 keV shield threshold, without PSD. Fluxes in cts cm^{-3} s^{-1} .

5.1.3 Background Gamma-Ray Lines

Background gamma-ray lines are emitted in passive materials close to the detectors and in the detector material itself. Primary and secondary cosmic ray particles (protons and neutrons) induce excited nuclei in nuclear reactions with nuclei of the passive material. The prompt or delayed (radioactive) de-excitation of these nuclei leads to gamma-ray lines which can be detected by the germanium detectors. Calculations show that lines originating in the mask should not pose a problem for SPI.

5.2 Instrumental Characterization and Calibration

The SPI instrument has been fully tested and calibrated on ground before the launch. Some tests and calibrations with radioactive sources were performed on ground with the full satellite. The

sensitivities, resolution, and other characteristics given in this document are the result of testing of parts of the instrument, testing of preliminary models of the instrument and careful model calculations. They represent the current best knowledge of the SPI instrumental characterization.

After launch the SPI team will check that the prelaunch calibration, as established on ground, is maintained. This is done during the initial in orbit phase (Commissioning Phase). Several observations are planned to check the imaging performance, spectroscopic performance, background, flux calibration (sensitivity) and the sensitivity to out of field sources. If any large changes are found, especially in the sensitivities, observers will be informed. Currently calibration observations of the Crab nebula and Cygnus X-1 are foreseen to provide the calibration that will be used for the data processing. Unfortunately the Crab nebula is not visible to INTEGRAL so only Cygnus X-1 can be observed during the Commissioning Phase. The Crab nebula will however be observed as soon as it becomes available. It is expected that the observation of Cygnus X-1 will provide an accurate calibration up to about 2 MeV, whereas the Crab nebula is needed to extend the calibration to higher energies. Currently the following observations of these targets are foreseen:

- Cygnus X-1:
  - 5 by 5 dithers on-source and two pointings 10 degrees off-source for 2.7 10^5 seconds each.
  - hexagonal dither with source on-axis for 2 10^5 seconds.
- Crab:
  - 5 by 5 dither centered on the source for 1.8× 10^5 seconds.
  - hexagonal dither centered on the source for 1.26× 10^5 seconds.

In Table 3 the expected accuracy for the hexagonal dithering observation of both sources for several energy bands in the range of the SPI instrument is given.

Energy band (MeV)		Back-	Cygnus X-1		Crab	
low	high	ground	Flux	σ	Flux	σ
0.04	0.1	8.56 10 $^{-2}$	2.28 10 $^{-1}$	2241	2.86 10 $^{-2}$	223
0.1	0.25	4.11 10 $^{-2}$	4.14 10 $^{-2}$	532	1.12 10 $^{-2}$	114
0.25	0.4	3.97 10 $^{-3}$	5.37 10 $^{-3}$	130	2.76 10 $^{-3}$	53.0
0.4	0.7	5.94 10 $^{-3}$	2.49 10 $^{-3}$	52.8	1.95 10 $^{-3}$	32.8
0.7	2.5	2.12 10 $^{-2}$	1.23 10 $^{-3}$	9.55	1.85 10 $^{-3}$	11.4
2.5	5.0	5.19 10 $^{-3}$	9.21 10 -5	0.99	3.51 10 $^{-4}$	3.0
5.0	8.0	1.52 10 $^{-3}$	2.04 10 -5	0.28	1.30 10 $^{-4}$	1.4

Table 3: Accuracy for calibration observations of Cygnus X-1 and the Crab nebula, using hexagonal dithering. The integration times are 2×10^5 and 1.26×10^5 seconds respectively. Calculations were done using the Observing Time Estimator. Fluxes are in ph cm^{-2} s^{-1}

After the Commissioning Phase the SPI team and the ISDC will calibrate the instrument using data taken during routine observations. This will allow an accurate determination of e.g. the background. Also lines originating in the BGO shield (511 keV, 6.1 MeV O line) can be used for calibration purposes (e.g. energy calibration), and lines that originate from materials inside the cryostat that have known intensities can be used to measure the Ge detector efficiency. The detector gains, thresholds and resolution versus energy are determined from normal event data and ACS off spectra (for consistency checks) in the routine monitoring task of ISDC. Finally, after every detector annealing a thorough check will be done of the instrument imaging and spectroscopic response, since these may change as a result of the annealing process.

5.3 Measured Performance

5.3.1 Imaging Resolution

The true imaging resolution will only be known after launch, since it depends on the background radiation. The design of the instrument however is such that the angular resolution for (isolated) point sources is about 2.5 °(FWHM). The location of point sources can be done with an accuracy better than this, but this depends on the strength of the source. As explained above, dithering is required, when imaging more complex regions.

5.3.2 Spectral Resolution

The spectral resolution has been measured in the laboratory with detectors that are representative of the flight units, and afterwards with flight model detectors and pre-amplifiers. An example spectrum obtained in this way is shown in Figure 4. The measured energy resolution as a function of energy for an individual detector is given in Figure 5. The energy resolution for the full instrument is given in Table 4. The energy resolution does not depend strongly on the temperature of the detectors, therefore even in the case of a failure of one of the coolers, the spectroscopic capability of the instrument is not significantly degraded. However a small drift in energy is observed as a function of temperature, so a recalibration would be required.

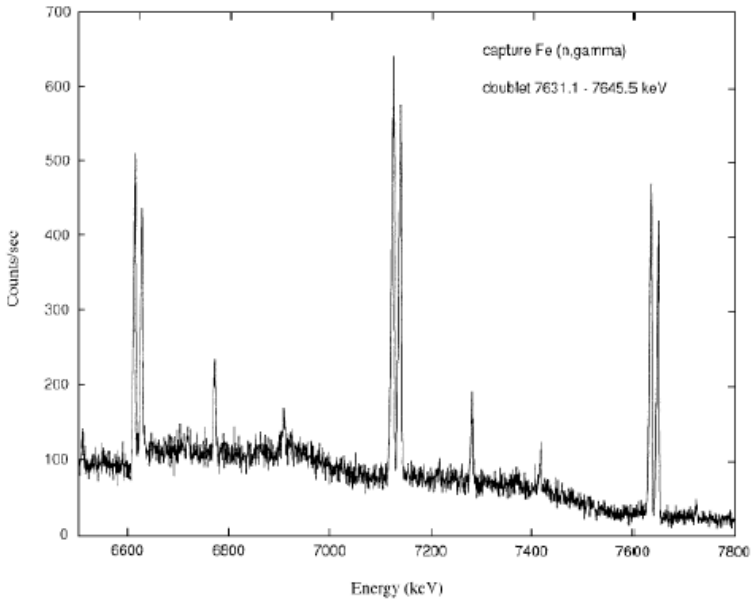


Figure 4: Example spectrum taken with laboratory detector units, representative of the flight units.

5.3.3 Sensitivity

The continuum and line sensitivities of the SPI instrument are given in Figure 6 and Figure 7. In Table 4 the instrument performance numbers (energy resolution, continuum and line sensitivities) are given at a number of energies in the SPI range. The sensitivities given in this table are 3 sigma in 10^6 seconds pure integration time, using a BGO threshold of 80 keV, a plastic scintillator threshold of 300 keV, and with PSD and multiple event reduction techniques applied (this is similar to the normal operating mode). The continuum sensitivities are for $\Delta E = E/2$, and are calculated from the narrow line sensitivity by dividing those by $\sqrt{R \cdot \Delta E}$ where R is the instrument resolution for lines. The line sensitivities are fluxes in photons cm $^{-2}$ s $^{-1}$, the continuum sensitivities are

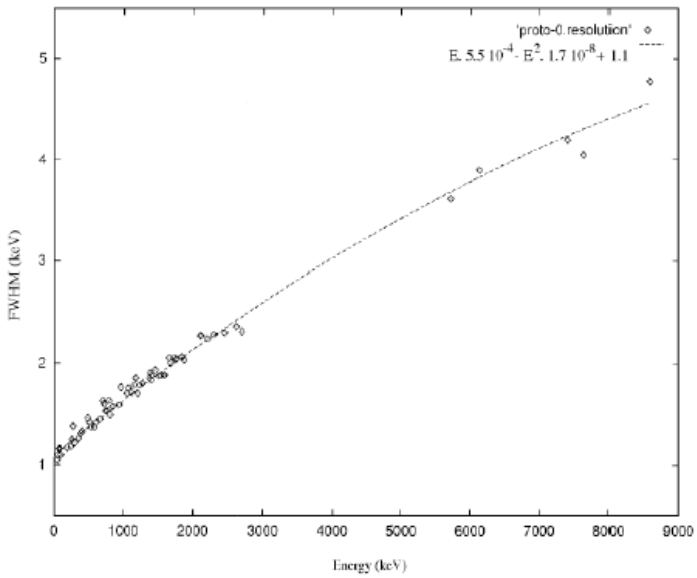


Figure 5: The measured energy resolution of an individual SPI detector. This was measured using laboratory detectors. The resolution of the full instrument with all 19 detectors is slightly lower than this.

fluxes in photons cm $^{-2}$ s $^{-1}$ keV $^{-1}$. The line sensitivities are for narrow lines. For broad lines, the sensitivity of the instrument degrades, as can be seen in Figure 8, where the factor is plotted with which the sensitivity is degraded as function of the energy for three line widths (1, 3 and 10% of the energy of the line). Note that the sensitivity for 511 keV is not given in Figure 7, but only in Table 4. The 511 keV sensitivity is worse than the surrounding continuum due to the strong 511 keV background line originating in the instrument.

5.3.4 Dithering Sensitivity Degradation

The instrumental sensitivities given in Table 4 and Figures 6,7 are for a source on axis, and do not take into account dithering. As stated earlier, observations with SPI should not be done in staring mode, since this makes the identification and removal of the background impossible. Dithering on the other hand has the disadvantage that the source is not observed for the full integration time in the center of the fully coded filed of view (center of the instrument response). The SPI response falls off towards the edge of the filed of view, and therefore dithering will degrade the sensitivity of the instrument somewhat. The hexagonal dither (a central pointing with six surrounding pointings in hexagonal pattern, all 2°apart) only samples the central part of the SPI fully coded field-of-view. Therefore no reduction in the sensitivity is noticeable. The 5 by 5 dither (a square pattern of 5 by 5 pointings around the source, all with 2°spacing) however samples closer to the edge of the fully coded field-of-view. In this case the sensitivity is degraded by a factor 0.8374 (i.e. the sensitivities given in Table 4 should be divided by this number to get the effective sensitivity).

5.3.5 Detection of off-axis-sources

The wide field-of-view of SPI allows the detection of off-axis sources. However it also means that off-axis sources will create a shadowgram on the detector that increases the background photons for the prime target. To remove this background a proper mapping of the source and the surroundings is necessary. This is the main reason why hexagonal dithering should only be used for isolated point sources, where no significant contribution is expected from other sources with about 20°. In order to allow the observer to estimate the significance of an off-axis detection, we give the

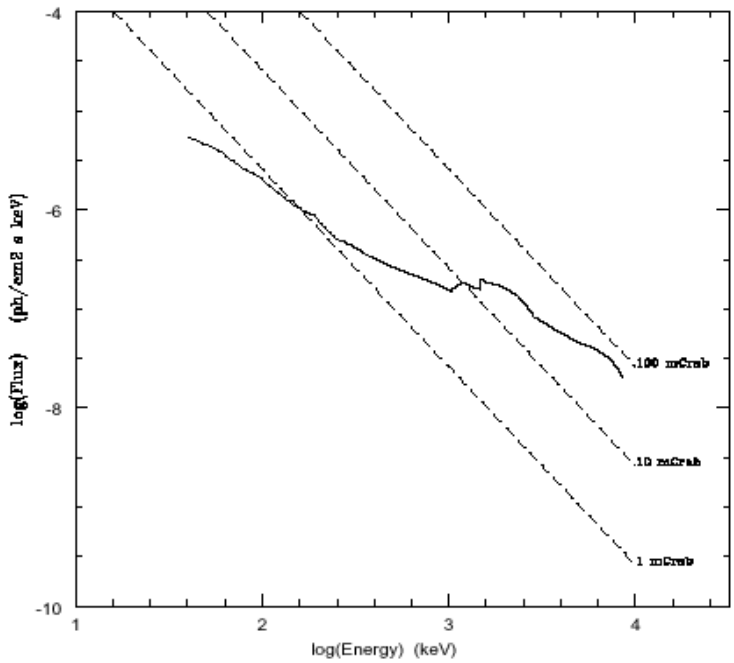


Figure 6: The continuum sensitivity of the SPI instrument for a 3 sigma detection in 10^6 seconds, on axis. The fluxes are for $E/\Delta E = 2$. The dashed lines indicate extrapolations from the X-rays using an powerlaw with photon index -2 for 1, 10 and 100 mCrab.

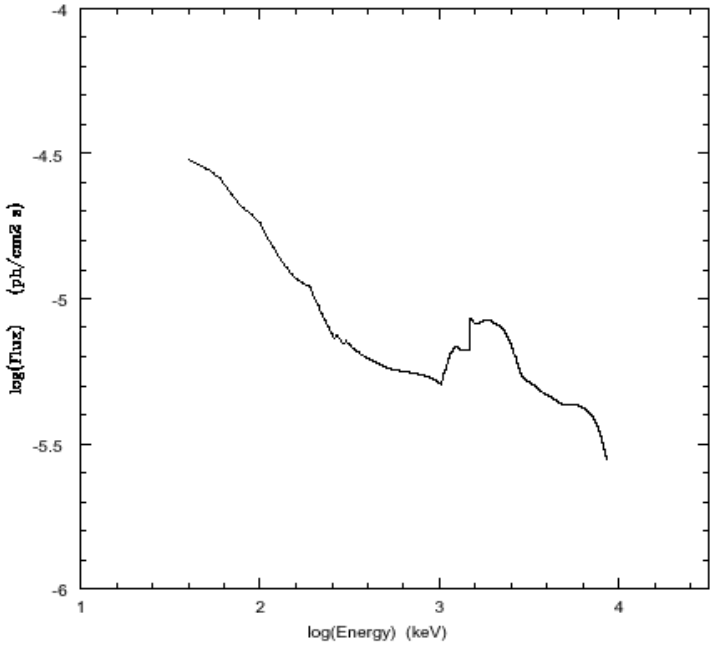


Figure 7: The narrow line sensitivity of the SPI instrument for a 3 sigma detection in 10^6 seconds. Note that the 511 keV line is not shown in this figure.

Energy (keV)	Resolution (keV)	Continuum sensitivity (ph cm^{-2} s^{-1} keV^{-1})	Line sensitivity (ph $cm^{-2}s^{-1}$)
50	1.531	$4.53 \cdot 10^{-6}$	$2.80 \cdot 10^{-5}$
100	1.563	$2.08 \cdot 10^{-6}$	$1.84 \cdot 10^{-5}$
200	1.654	$7.93 \cdot 10^{-7}$	$1.02 \cdot 10^{-5}$
300	1.76	$4.41 \cdot 10^{-7}$	$7.16 \cdot 10^{-6}$
400	1.85	$3.24 \cdot 10^{-7}$	$6.23 \cdot 10^{-6}$
500	1.926	$2.66 \cdot 10^{-7}$	$5.83 \cdot 10^{-6}$
511	1.933	$1.26 \cdot 10^{-6}$	$2.80 \cdot 10^{-5}$
600	1.992	$2.31 \cdot 10^{-7}$	$5.65 \cdot 10^{-6}$
700	2.051	$2.07 \cdot 10^{-7}$	$5.55 \cdot 10^{-6}$
800	2.106	$1.88 \cdot 10^{-7}$	$5.45 \cdot 10^{-6}$
900	2.158	$1.70 \cdot 10^{-7}$	$5.31 \cdot 10^{-6}$
1000	2.209	$1.54 \cdot 10^{-7}$	$5.11 \cdot 10^{-6}$
1100	2.257	$1.69 \cdot 10^{-7}$	$5.94 \cdot 10^{-6}$
1200	2.303	$1.81 \cdot 10^{-7}$	$6.74 \cdot 10^{-6}$
1300	2.347	$1.72 \cdot 10^{-7}$	$6.70 \cdot 10^{-6}$
1400	2.389	$1.62 \cdot 10^{-7}$	$6.62 \cdot 10^{-6}$
1500	2.432	$1.99 \cdot 10^{-7}$	$8.50 \cdot 10^{-6}$
1600	2.473	$1.85 \cdot 10^{-7}$	$8.21 \cdot 10^{-6}$
1700	2.513	$1.79 \cdot 10^{-7}$	$8.28 \cdot 10^{-6}$
1800	2.553	$1.76 \cdot 10^{-7}$	$8.41 \cdot 10^{-6}$
1900	2.593	$1.69 \cdot 10^{-7}$	$8.39 \cdot 10^{-6}$
2000	2.634	$1.62 \cdot 10^{-7}$	$8.29 \cdot 10^{-6}$
2250	2.73	$1.42 \cdot 10^{-7}$	$7.85 \cdot 10^{-6}$
2500	2.821	$1.18 \cdot 10^{-7}$	$6.99 \cdot 10^{-6}$
2750	2.91	$9.25 \cdot 10^{-8}$	$5.85 \cdot 10^{-6}$
3000	2.997	$7.88 \cdot 10^{-8}$	$5.28 \cdot 10^{-6}$
3500	3.162	$6.62 \cdot 10^{-8}$	$4.93 \cdot 10^{-6}$
4000	3.32	$5.69 \cdot 10^{-8}$	$4.64 \cdot 10^{-6}$
4500	3.471	$5.04 \cdot 10^{-8}$	$4.45 \cdot 10^{-6}$
5000	3.616	$4.51 \cdot 10^{-8}$	$4.28 \cdot 10^{-6}$
5500	3.757	$4.24 \cdot 10^{-8}$	$4.31 \cdot 10^{-6}$
6000	3.889	$3.96 \cdot 10^{-8}$	$4.28 \cdot 10^{-6}$
6500	4.018	$3.64 \cdot 10^{-8}$	$4.16 \cdot 10^{-6}$
7000	4.141	$3.30 \cdot 10^{-8}$	$3.97 \cdot 10^{-6}$
7500	4.26	$2.91 \cdot 10^{-8}$	$3.68 \cdot 10^{-6}$
8000	4.376	$2.48 \cdot 10^{-8}$	$3.28 \cdot 10^{-6}$

Table 4: The energy resolution (FWHM), narrow line and continuum sensitivities of the SPI instrument. (3σ detection in 10^6 seconds)

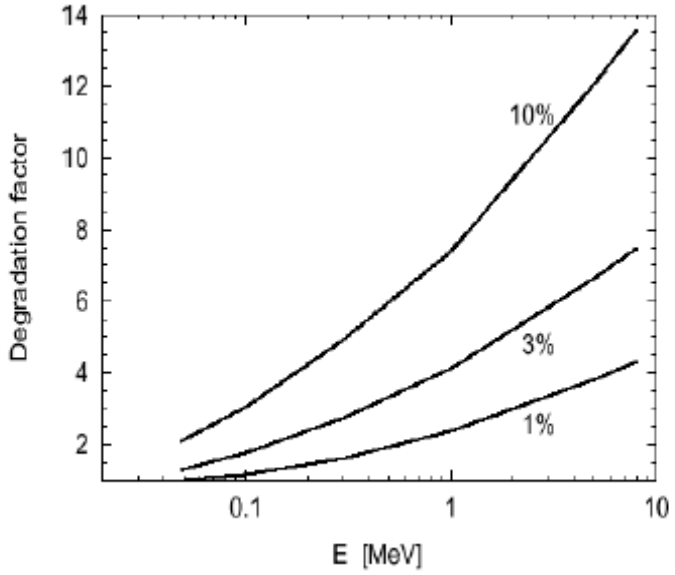


Figure 8: The degradation factor of the line sensitivity for broad lines (with a width of 1, 3 and 10% of the line energy) as a function of energy.

reduction factor for the sensitivity for hexagonal and 5 by 5 dithers in Table 5 . The reduction for staring is similar to the one for hexagonal dithers. Observers can calculate the effective sensitivity by dividing the sensitivity limits given in Table 4 by the factor given in Table 5.

Off axis distance (degrees)	Sensitivity degradation	
	hexagonal	5 by 5
0	1.0	0.8374
1	0.6655	0.7925
2	0.7638	0.8004
3	0.6838	0.7879
4	0.7147	0.7874
5	0.7056	0.7746
7.5	0.6309	0.7357
10	0.5505	0.6718
12.5	0.4938	0.5918
15	0.3749	0.5002
17.5	0.1888	0.3774
20	0.0886	0.2047
25	0.0	0.0148
30	0.0	0.0

Table 5: Sensitivity degradation factor as function of the distance off-axis for a hexagonal and a 5 by 5 dither pattern.

5.3.6 Imaging Capabilities

The values presented in Table 4 are for an identified point source (i.e. a 3σ excess in a pixel). However for unknown sources in an image of an area of sky, the situation is slightly different. In a map containing a large number of pixels, the probability that an n-sigma excess will occur by chance somewhere in the map can be significantly higher than suggested by the integral error function. In a SPI map covering, say 25×25 degrees there are approximately 60 independent

pixels. Thus 99% confidence that a source at a specific position (a known source) is real requires 2.35 sigma, whereas 99% confidence that a source found at an arbitrary position somewhere in the field (an new unknown source) is real requires 3.6 sigma significance. Therefore to identify new, unknown sources in the field-of-view, a higher significance is required than for an unknown source in the field-of-view (since probability for an chance n-sigma excess due to noise somewhere in the map is higher).

5.3.7 Timing Capabilities

The instrument works in photon by photon mode. Each photon data set includes timing information given by a 100μs clock signal. This clock is synchronized to the on board clock, and thus to the UTC. The timing error budget for SPI is derived from:

- the accuracy of the on-board clock and the synchronization,
- the conversion between on-board time and UTC,
- the conversion between UTC arrival time at the spacecraft and the arrival time at the solar system barycentre.

The resulting SPI timing accuracy calculated in this way is 129μs, 3σ accuracy, and a 90% confidence accuracy of 94μs.

Part II

Data Analysis

6 Overview

Each photon that is absorbed in a SPI Ge detector gives a pulse that is sent to the electronics. The electronics analyse the incoming pulses and the veto signals and tags each photon with the energy, the time and the type of event (i.e. single detector events with or without PSD and multiple detector events). These data are then sent to the ground.

During the Pre-Processing the information contained in the TM packets is written into a set of FITS formatted data files (RAW data). Pre-Processing produces a set of RAW data files for each Science Window.

After the Pre-Processing the Science Window Pipeline converts the local on-board time (LOBT) to the common on-board time (OBT) and derives the true multiplicity of the event. This information is written to the set of prepared (PRP) data files for each Science Window.

All the previous steps are done at ISDC and can't be redone by user. That's why we describe it only briefly and in the following sections we concentrate on the Scientific Analysis. The different tasks of Scientific Analysis are summarized in Figure 9.

The three or four big letters indicated in the boxes give the task acronyms. It starts with an observation group of prepared data. The subsequent resulting data are shown on the right, and after each step the newly created data are attached to the observation group. Any data of the observation group can then be used as an input for later tasks.

The task **Build Observation Group** creates prepared ISDC Observation Groups (OG) according to such criteria as time intervals, sky coordinates, instrument modes, list of Science Window Groups (SWGs) IDs etc... or a combination of them. The Observation Group points to an index of science windows related to a number of prepared Science Window Groups.

The tasks displayed in Fig.9 are described in some details below.

COR – Data Correction

(1) Computes the event energy in keV from the channel energy (PHA) using a calibration index file, and (2) derives a ground-derived PSD localized/unlocalized flag from the PSD prepared data. (This task is fulfilled by he executable *spi_gain_corr*)

POIN – Pointing Definition

Defines a number of time periods during which the S/C attitude can be considered as constant for SPI analysis (e.g., a slew can be splited into a number of periods) and extracts the spacecraft attitude information from the input group. Store the results in a pointing file for further use.(*spipoint*)

GTI – Good Time Handling

Generates, selects, and merges Good Time Intervals to produce a unique GTI which is to be used for selecting good events. The ON_TIME, i.e., the total net observation time within the good times in seconds is also computed. Different GTIs can be derived for different detectors. Therefore, at this level user must define the list of detector to be used in the analysis, and subsequent tasks (*spidead, spiback, spihist*) must read the detector list from the GTI table. Detectors are defined according to the pseudo detector scheme. (*spi_gti_creation*)

DEAD – Dead and Live Times

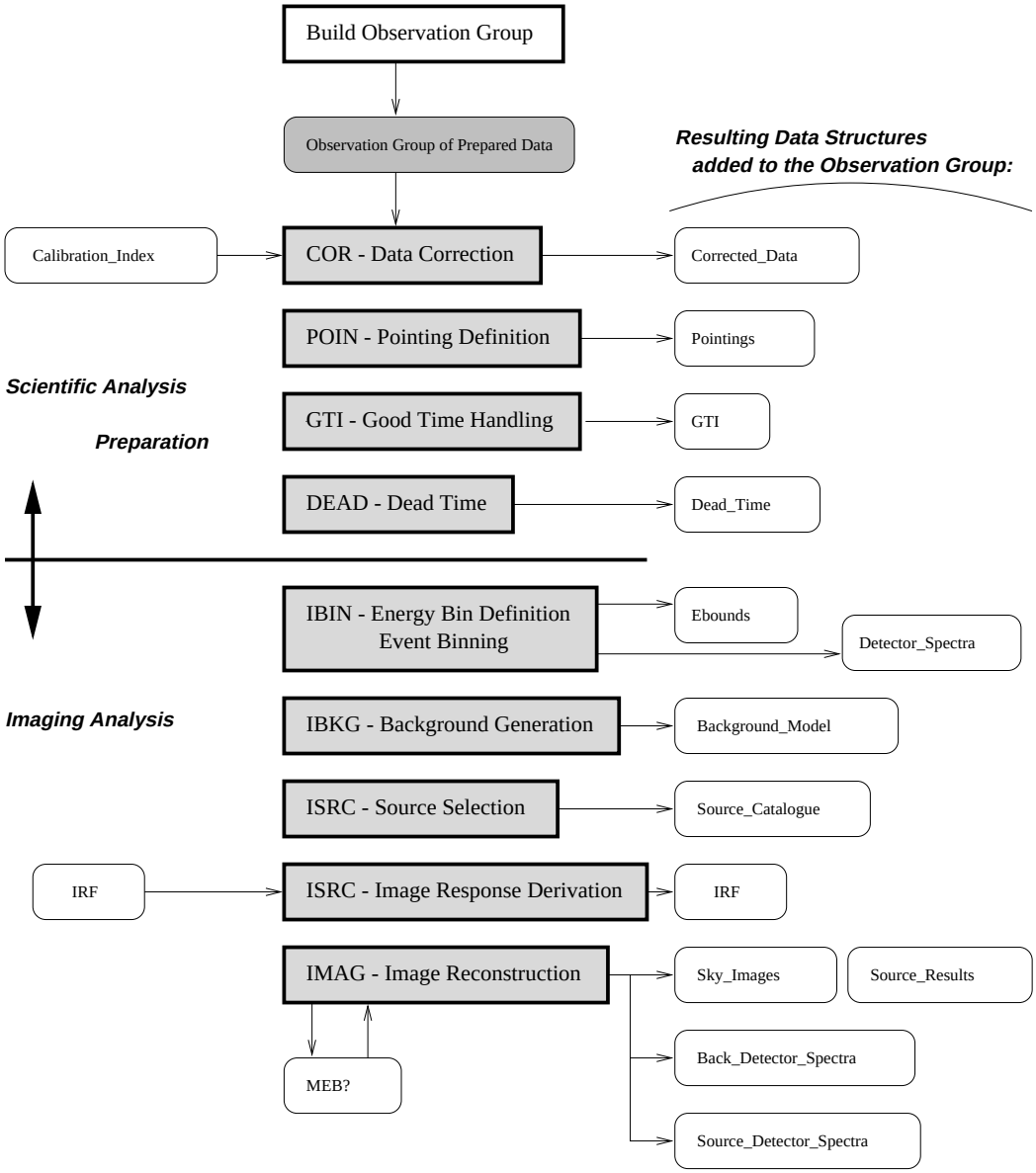


Figure 9: Scientific Analysis Preparation and Imaging Analysis

Computes the ratio of the dead time to the live time ("dead ratios") and live times within the good time interval for all detectors and pseudo-detectors.(*spidead*)

BIN_I – Event Binning for Imaging

Defines the energy bins to be used for imaging, selects good events within the GTI, and creates detector spectra for all detectors and pseudo-detectors. Spectrum values are express in **counts**, or in **rates** dividing counts by the live times. (*spibounds*)

BKG_I – Background Generation for Imaging

Derives estimated background detector spectra from models or observation data and stores them in a background data structure.(*spiback*)

CAT_I – Catalogue Source Selection for Imaging

Selects a list of known sources from the ISDC reference catalogue, or from previous analyses, and creates a source data structure, containing source location and expected flux values.

RSP_I – Image Response (IRF) Derivation

TBD

IMA – Image Reconstruction

Generates sky images and search for significant sources. If sources are detected, a new source data structure is created, including a copy of the input source data, and the newly derived source properties, such as source positions and fluxes.(*spiskymax, spiros*)

7 Low Level Processing Data Products

7.1 Event Types

The photon which entered the telescope can be detected due to its interaction with the absorbing material of the detector. Three major types of interactions play a dominant role: photoelectric absorption, Compton scattering and pair production. In the photoelectric absorption process a photon undergoes an interaction with an absorber atom in which the photon completely disappears. In its place an energetic photoelectron is ejected by the atom. The photoelectron carries off most of the original photon energy. The Compton scattering takes place between the incident gamma-ray photon and an electron in the absorbing material. The incoming photon is deflected and it transfers a portion of its energy to the electron. The energy transferred to the electron can vary from zero to a large fraction of the initial gamma-ray energy. In the pair production process the gamma-ray photon disappears and is replaced by an electron-positron pair. The positron will annihilate in the absorbing medium and two annihilation photons are normally produced as secondary products of the interactions. Depending on the size of the detector and on the energy of the incoming photon, a photon scattered in a Compton interaction can escape the detector, or undergo a second interaction. The pairs of 511 keV photons, produced by the annihilation of the positrons resulting from pair creation, can also produce other interactions or escape the detector.

In SPI the detector array is used to recover the total energy of an incoming photon. This contributes to raise the full-energy peak and to reduce the Compton continuum. Unfortunately it also degrades spatial information as it is not possible, in general, to determine which detector was hit first.

All the signal output data produced from the detection plane are also directed towards PSD which, by analysis of the signal shape, is able to minimize the background in the range 200 keV - 2 MeV. By comparing the form of impulsions produced by the pre-amplifiers of the detectors with the profiles archived in a library, the PSD system determines whether the measured shape is best represented by a single or multiple shapes and consequently whether the signal was localized or not. This classification allows an effective rejection of background events that arise from localized beta-decays within the SPI Germanium detectors.

During the detector life, its characteristics could change and consequently the shapes of the events evolve. This is the reason why the shapes must be analyzed continuously. The shapes evolution could lead to build a new reference shapes library. From time to time, it is necessary to have a large selection of samples. One curve is downloaded each 4 seconds. Several thousands of simple pulses per detector are necessary for checking or rebuilding a new library. Then the new library will be uploaded.

All events detected by SPI are classified in accordance with how many detectors respond to an incoming photon. The event detected by only one detector is called either *PSD event* or *single event* according to whether it was processed by PSD or not. Multiple events are detected by several detectors and the value of multiplicity corresponds to the number of the detectors hit. Events that were detected only by PSD are called *pure PSD events*.

7.2 Raw Data

All scientific event and PSD curve data formatted as blocks are transmitted in 4 telemetry packets of identical structure, corresponding to the operational, emergency, calibration and diagnostic modes. (The packets corresponding to the modes that do not occur are empty). Two raw data files are created for each pointing - **spi_raw_block.fits** for the house keeping data and **spi_raw_oper.fits** for the event data. In the following we descibe the analysis of the operational mode only, as it is the only mode important for the Science Data Analysis.

The file **spi_raw_oper.fits** includes 14 substructures. Each data substructure corresponds to one type of event. The names of the data structures and the corresponding event types are presented

Table 6:

Event Type	spi_raw_oper.fits Raw Data Structure	spi_prp_oper.fits Prepared Data Structure	spi_cor_oper.fits Corrected Data Structure
SINGLE	SPI-OSGL-RAW	SPI-OSGL-PRP	SPI-OSGL-COR
PSD	SPI-OPSD-RAW	SPI-OPSD-PRP	SPI-OPSD-COR
PSD CURVE	SPI-OCRV-RAW	SPI-OCRV-PRP	SPI-OCRV-COR
MULTIPLE (2)	SPI-OME2-RAW	SPI-OME2-PRP	SPI-OME2-COR
MULTIPLE (3)	SPI-OME3-RAW	SPI-OME3-PRP	SPI-OME3-COR
MULTIPLE (4)	SPI-OME4-RAW	SPI-OME4-PRP	SPI-OME4-COR
MULTIPLE (5)	SPI-OME5-RAW	SPI-OME5-PRP	SPI-OME5-COR
MULTIPLE (>5)	SPI-OMEH-RAW	SPI-OMEH-PRP	SPI-OMEH-COR
MULTIPLE PSD (3)	SPI-OMP3-RAW	SPI-OMP3-PRP	SPI-OMP3-COR
MULTIPLE PSD (4)	SPI-OMP4-RAW	SPI-OMP4-PRP	SPI-OMP4-COR
MULTIPLE PSD (5)	SPI-OMP5-RAW	SPI-OMP5-PRP	SPI-OMP5-COR
MULTIPLE PSD (6)	SPI-OMP6-RAW	SPI-OMP6-PRP	SPI-OMP6-COR
MULTIPLE PSD (> 6)	SPI-OMPH-RAW	SPI-OMPH-PRP	SPI-OMPH-COR
PURE PSD	SPI-OPPS-RAW	SPI-OPPS-PRP	SPI-OPPS-COR

in Table 6. The information about the multiple events processed by PSD is added to the multiple event data structure as well as to the multiple event processed by PSD data structure, so that the last one contains redundant information and is not used for the scientific processing of the data. The data structure for pure PSD events and the one with examples of the PSD curves for the random events are also used for internal purposes only.

All raw event data structures used for scientific analyses are binary tables which contain such event information as the time-tag (local SPI time of the event), number and channel of detectors hit (in the table this columns are labeled TIME_TAG, DETE and PHA correspondingly). The data structures for the multiple events contain also the information about the multiplicity of the event and the time delay between the detectors (columns MULT and DELTA_TIME).

The data structure for PSD event additionally contains the column with PSD flag (it is equal to 0 for localized events and to 1 for unlocalized events) and the compressed PSD data (columns PSD_RAWFLAG and PSD_DATA).

7.3 Prepared Data

The main task of the Science Window Pipeline is to prepare raw data for the following Scientific Analysis. It converts the HK parameters into the physical units and makes some corrections and transformations of the raw data that are not included in Pre-Processing (because they involve alteration of data format or use additional parameters that do not come from the telemetry data flow).

As a result the file **spi_prp_oper.fits** is created. This file, like the file with raw data, also contains 14 substructures, listed in the Table 6. All these data structures are binary tables with the absolute-time information (column OB_TIME). The data structure for PSD events also contains the unpacked PSD information about the form of the pulse shape - the flag, equal to 0 in case if the PSD analysis were done without internal errors, the positions of the two highest peaks of the pulse curve and the ratio of their amplitudes (columns PSD_ERR, PSD_TTP1, PSD_TTP2 and PSD_AMP). The data structures for multiple events besides the time information contain column with the information about the event true multiplicity (column MULT_FLAG). This multiplicity can differ from that in the raw data if during the low-level analysis it was decided for some reasons to redefine the time interval during which the signal measured by different detectors is assumed to

be related with the same incident photon.

7.4 Instrument Characteristics used in Data Analysis

In order to process your RAW and PRP data you need to know the instrument response and the results of the Calibration Analysis made at ISDC.

7.4.1 Instrument Calibration

During the Instrument Calibration the measured and expected energies, width and channel positions of the lines used in Calibration Analysis are compared.

The results of the Calibration Analysis performed at ISDC are written to the file **spi_gain_coeff.fits**. The data structure **SPI.-COEF-CAL** contains gain coefficients. For a given OBT start – stop, and energy range, the different coefficients connecting the channels and energies are stored as 19 vectors (one for each detector).

7.4.2 Instrument Response

RMF data structures

Figure 10 presents a few definition used it the following discussion. Np and Ep are the number and the energy of the incoming photons, and Nc(i) and the Ec are the number of the counts and the energy measured in the detector, respectively.

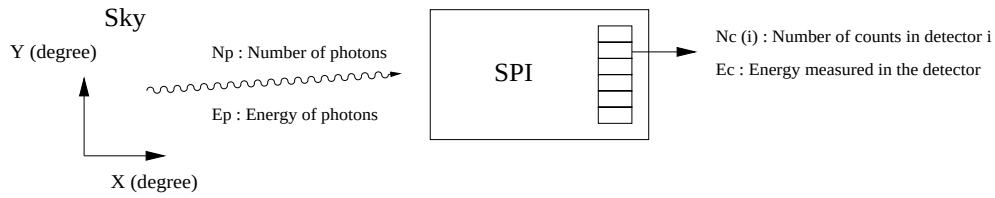


Figure 10: Some definitions used in the response description

In order to reduce their size and to speed up the processing, the response matrices are decomposed into two sets of files, the ancillary response files (ARFs) and the redistribution matrix files (RMFs) following the XSPEC paradigm. The ARFs describe the geometrical factors with effective areas (in cm^2) per input photon-energy (Ep) bin. The RMF are decomposed into three categories as illustrated in Fig. 11. A first RMF described the full-energy peak, a second, the Compton continuum with the events interacting first in the detectors, and a third, the Compton continuum with the event interacting first in the passive material inside the shield. These RMFs are to a good approximation independent of detector and direction.

Three corresponding ARF sets are defined and the final response is a linear combination of the AFR and the RMF coefficients.

RMF file **spi_rmf_response.fits** contains data structures for each kind of RMF and an EBOUNDS extension, as it is shown in Figure 12.

The columns N_GRP, F_CHAN, and N_CHAN are used for a simple compression scheme, which alleviates the necessity of storing redundant zero value elements, and which can be understood with a glance at Fig. 13. LO_THRES is stored as a keyword in the RMF data structure.

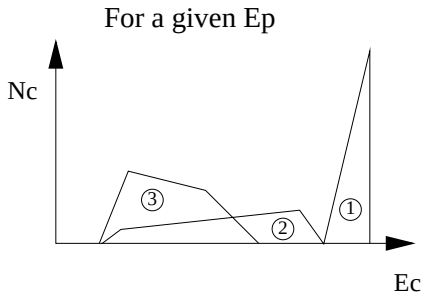


Figure 11: Schematic illustration of the three RMF types

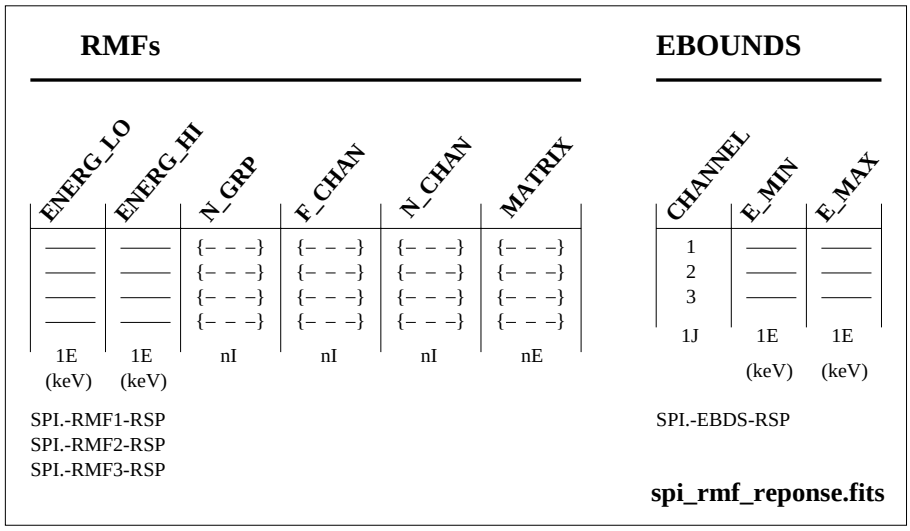


Figure 12: Format of the RMF file

IRF data structures

In the case of the instrumental response for image reconstruction, a complete set of ARFs coefficients for a given photon energy (Ep) is stored as a 4-dimensional image called an Image Response File (IRF) in a **SPI.-IRF.-RSP** data structure. An IRF image has (1) a detector axis, (2) a zenith equidistant FOV X-axis, (3) a zenith equidistant FOV Y-axis, and (4) an axis to store the three types of ARF.

In addition, IRFs for several, independent regions are derived and stored in different data structures. This is to allow for different bin sizes for different regions. For example in the current implementation, the bin size in x-y in the Field Of View (FOV) is thinner than the one outside the FOV.

An index **SPI.–IRF.-RSP-IDX** links a complete set of IRFs (*i.e.,* , a 2-D grid for a complete set of photon energies and region numbers), while a group relates the index to the corresponding three RMFs.

ARF and RMF for spectral analysis with XSPEC

In the case of spectral analysis, only the instrumental response for a few positions in the sky (the positions of the considered sources) needs to be characterized. Therefore, the ARFs do not need

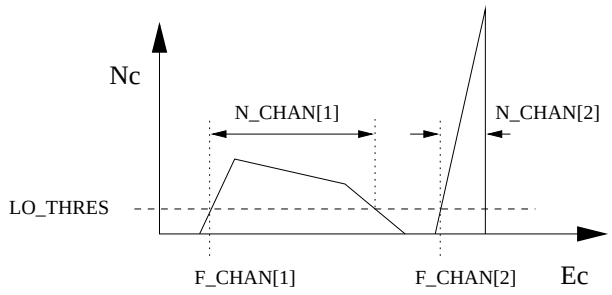


Figure 13: Illustration of the RMF compression scheme with a N_GRP=2 case

to cover the full (x, y) plane. However, as the source relative position depends on the location of the pointings a set of ARF is required for each of them.

In this case, the ARF coefficients are stored following the scheme used for the detector spectra. For each pointing and for each detector, three vectors contains the different ARF (ARF1, ARF2, ARF3) coefficients for the different photon-energy. A set of three vector columns correspond to one source. In the case of XSPEC multi-sources spectral fitting, one set of three columns should be generated for each of the considered sources.

Unlike the ARFs stored as IRF, the above ARFs are fully specific. They should be derived for each observation, and they cannot be re-used.

As the RMFs are assumed to be independent of detector and direction, a generic set can be used. Their format is as shown above, however, the number of rows of the RMF should match the number of element of the ARF vectors. They both represent the number of photon-energy bins considered.

8 Scientific Analysis

There is a simple way to run Scientific Analysis. You should just set parameters (in the parameter file spi_osa.par) and run the script *spi_osa*. We will speak about the script a little bit later in the cookbook chapter, at first we want to present you the decomposition of the script in order to explain how it works and what parameters you are to enter.

There are several ways of entering the parameters - you can modify the parameter file itself (the explanation of what is the parameter file can be found in the [1], Section "Software Tools") (you can find all the parameter files in the directory **pfiles/**), input them from the command line or use a Graphical User Interface (GUI). From the command line you should enter those parameters that are not defined as hidden in the parameter file (see below). With a GUI you can see all parameters when you select an option "Show hidden parameters".

Most of the executables described below have different set of parameters - you can use them in a pipeline as it is done in the script, or separately. If you specify an observation group as input parameter then the program works with all the science windows - members of the group. As an output executables can either produce new files and groups or modify the existing ones. If the input observation group is not specified then the output observation group is also taken as an input one.

Describing the executables we give as an example set of the parameters that will allow you to perform a first try of data analysis. If there is no example after the parameter description then you should enter "" instead of the **Value**.

8.1 Pseudo-detectors Definition

In image reconstruction and spectral extraction processes, PSD events and multi-detector events are binned into a number of *pseudo-detectors*. Thus the different kinds of events are treated as being detected by other than the "physical' detectors. This allows to treat them independently. for example each pseudo-detector has an individual response function, dead time, and so on. Pseudo-detector numbers are defined as follow.

Table 7:

Pseudo Detector Number	Pseudo Detector ID	Description
#0 - #18	0-18	numbers for the single and the PSD (any flag) events.
#19 - #60	20001 - 21718	pseudo detectors for the double events.The first digit of the ID, indicating the multiplicity (i.e., 2), is followed by four digits, two for each detector numbers. E.g., double events which hit detectors 4 and 15 are binned into pseudo-detector number 20415.
#61 - #84	3000102 - 3061718	are pseudo detectors for the triple events. The first digit of the ID, indicating the multiplicity (i.e., 3), is followed by six digits, two for each detector numbers. E.g., triple events which hit detectors 0, 13 and 6 are binned into pseudo-detector number 3001306.
#85 - #103	1900 - 1918	are pseudo-detector numbers for the single events, excluding PSD events.

#104 - #122	1000 - 1018	are pseudo-detector numbers for the events with PSD flag = 0, i.e., localized events.
#123 - #141	1100 - 1118	are pseudo-detector numbers for the events with PSD flag = 1, i.e., events with energy deposits at different locations in the detector.

8.2 Build Observational Group *−og_create*

The first step for the Scientific Analysis of the SPI data is the creation of the observation group (OG). This task is fulfilled by the program *og_create* which produces an observational group of PRP level out of an index of science windows groups or a list of SWG DOLs. Figure 14 gives an example of such a list written to the ASCII file dols.txt.

dols.txt

```
scw/0002/000200000022.000/swg_prp.fits[1]
scw/0002/000200000032.000/swg_prp.fits[1]
scw/0002/000200000042.000/swg_prp.fits[1]
scw/0002/000200000082.000/swg_prp.fits[1]
scw/0003/000200000012.000/swg_prp.fits[1]
scw/0003/000200000032.000/swg_prp.fits[1]
scw/0004/000200000042.000/swg_prp.fits[1]
scw/0004/000200000082.000/swg_prp.fits[1]
```

Figure 14: example of a input list of SWG DOLs for *og_create*

og_create also creates the standard **obs** branch of the directory tree, where the following analysis will be performed, and the high-level science window groups will be produced.

To run this program you should specify the following parameters:

Name	Type	Description
Parameters defining the name, contents and location of the OG		
idxSwg	string	Index of science window group or ASCII list of SWG DOLs (see Figure 14)
ogid	string	Observation group id (used to build the path)
baseDir	string	base directory from which the obs branch will be build This parameter should be a relative path from where og_create is run.
instrument	string	Comma separated list of instruments. This will create several OG in the same repository. INTEGRAL → all data SPI, IBIS, JMX1, JMX2, OMC → Specific data

Additional parameters		
purpose	string	Scientific purpose of the OG (optional)
versioning	integer	Add a version to the **ogid** directory (0 = NO, 1 = YES) 0 is the default value

Example: og_create idxSwg="dols.txt" ogid="obs_id" baseDir="." instrument="SPI"

8.3 SPI Correction – *spi_gain_corr*

SPI correction uses calibration data described in Section 7.4.1 to compute the event energy in physical units (keV) from the instrumental channel (PHA). No event randomization is included in this process, i.e., the exact energy of the channel center is attributed to all events of a given PHA channel.

To run this program you should specify the following parameters:

Name	Type	Description
Input		
prpOG	string	DOL of the Prepared Observation Group to work with (e.g. og_spi.fits[GROUPING])
inSWG	string	DOL of the PRP SWG (optional), in case only one SWG should be corrected instead of a whole observation group
Output		
coeffDOL	string	DOL of the calibration file containing the correction parameters (e.g. "spi_gain_corr/spi_gain_coeff.fits[SPI.-COEF-CAL]")
outfile	string	Output file (optional) in case the input OG/SWG should not be modified
Additional parameters		
clobber	boolean	Decides if existing output data are to be overwritten or not

The result of the correction is written to the file spi_cor_oper.fits in the **scw** directory structure. This file like the file with raw and prepared data contains 14 substructures, one per event type, listed in the table 6. All these data structures contain the information about the event energy in keV (column ENERGY).

8.4 Pointing Definition – *spipoint*

The executable *spipoint* defines time intervals with stable enough attitude during the observation. Stable means that the attitude did not vary more than a tolerance value given as an input parameter. In a first approximation, the periods of stable attitude during an observation are the ISDC pointing science windows, but their exact boundaries will depend on the specified attitude

tolerance. The slew can also be divided into a number of relatively small intervals during which the attitude is stable within the given tolerance.

Name	Type	Description
		Input/Output
rogroup	string	DOL of the read only group for input
rwgroup	string	DOL of the read/write group for input and output (e.g. "og_spi.fits[GROUPING]")
pointing_dol	string	output pointing data structure (e.g. "pointings.fits(SPI.-OBS.-PNT.tpl)"
		Stability parameters
xtol	real	Tolerance on the stability of the X axis, in arc-minutes (e.g. 1.0)
ztol	real	Tolerance on the stability of the Z axis, in arc-minutes (e.g. 1.0)
		Additional parameters
clobber	boolean	Defaults to yes. Lets you overwrite the pointing structure

The *spipoint* output file in the directory **spi/**(e.g. **spi/pointings.fits** in the given example) contains in a data structure **SPI.-OBS.-PNT** an information about ISOC and SPI pointing ID (columns PTID_ISOC and PTID_SPI), the OBT and ISDC-JD start and end time of the period (columns OBT_START, OBT_END, TSTART and TSTOP), the duration of pointing in seconds (column TELAPSE) and the attitudes of the SPI X and Z axes (columns RA_SPIX, DEC_SPIX, RA_SPIZ and DEC_SPIZ). The schematic representation of this data structure can be found in Figure 15.

8.5 SPI Good Time Handling – *spi_gti_creation*

spi_gti_creation selects criteria for defining the good time and derive the Good Time Interval (GTI) to be used for event selection in the current analysis. Also the detectors and event types which will be used for the analysis are defined here.

Name	Type	Description
rwgroup	string	DOL of the read/write group for input and output (e.g. "og_spi.fits[GROUPING]")
rwgti	string	output GTI data structure (e.g. "spi/gti.fits(SPI.-OBS.-GTI.tpl)")

det_id	string	List of detectors and pseudo detectors used for the analysis. '-1' will give all single + PSD events (detector 0 to 18). Detector IDs up to 141 are allowed (see Table 7).Individual detectors are specified by their detector numbers separated by commas. A range of detector numbers can be specified by giving the first and last detectors in the range separated by a "-". (e.g. 0-84)
good-time-index-file	string	good time index file (without template or DOL!) (e.g. "goodtimeindex.fits")

For each SPI pointing (column PTID_SPI) and each detector and pseudo-detector (column DET_ID) the output GTI data structure SPI.-OBS.-GTI in the file **spi/gti.fits** contains the start and end times of the GTI (columns OBT_START, OBT_END, TSTART and TSTOP) and the total good time in seconds (column ONTIME). The schematic representation of this data structure can be found in Figure 15.

8.6 Dead Time and Live Time – *spidead*

The executable *spidead* computes the dead and the live times for each SPI pointing and each detector (and pseudo-detector) within the good time intervals defined by the SPI GTI file. The dead times are defined by the DFEE. It is assumed that the dead times do not depend on event energy.

The dead times for the double events are defined by the larger dead time of the two detectors involved. Also for the triple events the detector with the largest dead time involved in the triple determines the deadtime chosen for this pseudo detector.

Name	Type	Description
Input/Output		
in-og-dol	string	Input Observation Group DOL
dead-time-dol	string	Output dead time data structure (e.g. "spi/dead_time.fits(SPI.-OBS.-DTI.tpl)")
out-og-dol	string	Input/Output Observation Group DOL (e.g."og_spi.fits[GROUPING]")
deadtimecorrection	real	fraction of livetime of the instrument (for all pseudo detectors) If this parameter is set to a value > 0.0 then this is used as a fixed dead-time correction value (e.g. 0.98 for 98% of the time the detector was alive). If this parameter is 0.0, the correct dead times are determined automatically from the housekeeping data. If this parameter is -1, the dead time is only determined for one detector correctly and this value is used for all detectors. e.g. 0.98
Input in case you want to run a *spidead* for one science window only		
swg-index-dol	string	corrected swg index DOL
gti-dol	string	Good Time Interval DOL
Additional parameters		

clobber	boolean	Defaults to yes. Lets you overwrite the GTI structure.
chatter	integer	Chatter Level, varies from 1 to 100. Choose a higher chatter level for more logbook information. (e.g. 20)

Created file **spi/dead_time.fits** contains the data structure SPI.-OBS.-DTI. This data structure is a FITS table with two columns – DEADRATIO and LIVETIME. The DEADRATIO is a fraction of time during which the detectors are alive. The relation between ONTIME, DEADRATIO and LIVETIME is as follow

$$LIVETIME = DEADRATIO * ONTIME$$

The schematic representation of this data structure can be found in Figure 15.

8.7 Energy Bin Definition – *spibounds*

The executable *spibounds* is used to construct energy boundaries to be used for the binning of SPI event data.

Options include uniform linear or logarithmic spacing, as well as superimposing sub-regions (e.g. of finer spacing) over a global binning scheme so that you can investigate more carefully particular spectral regions (e.g., for spectral regions likely to contain line emission).

Name	Type	Description
Input/Output		
in-og-dol	string	DOL of the input fits file which identifies the observation group to be processed.
energy-boundaries-dol	string	Output FITS table (written to the output observation group) containing the energy bin boundaries specified by the user. (e.g. "spi/energy_boundaries.fits(SPI.-EBDS-SET.tpl)")
out-og-dol	string	DOL of the output observation group (e.g. "og_spi.fits[GROUPING]")
You can specify the output file		
outfile	string	The name of the output file with the bin boundaries.
in case you want to run *spibounds* for specific science windows		
swg-index-dol	string	DOL of the input FITS file containing the index of science windows to be analyzed.
gti-dol	string	DOL of the input FITS file containing the list of good-time intervals for each detector and pointing.
deadtime-dol	string	DOL of the input FITS file containing the list of deadtime correction factors and livetimes for each detector and pointing.

ebounds-dol	string	DOL of the FITS table containing the energy bin boundaries
parameters to define the energy binning		
nregions	integer	Number of regions (in energy space) for which distinct binning algorithms are to be defined. (e.g. 3)
regions	string	The boundaries of the energy regions, separated by commas. (e.g. 1325,1340,1165,1180)
nbins	string	The number of bins per region, separated by commas. Negative numbers indicate logarithmically space bins. (e.g. 15,3,15)
bintype	string	The type of bin boundaries to construct: photon (PI), detector pulse_height (PHA). Default is photon.
you can also define energy binning from file		
binfile	string	Optional input file containing energy-bin boundary definitions.
Additional parameters		
clobber	boolean	Defaults to **yes**. Option to whether overwrite existing files or not.
chatter	integer	Chatter Level, varies from 1 to 100. Default level is 20.
telescope	string	Telescope name. Default is "INTEGRAL"
instrume	string	Instrument name. (e.g. "SPI")

In the energy boundary file **spi/energy_boundaries.fits**, the energy channels can either be defined in energy units, with E_MIN and E_MAX, or in instrumental channel units, with PHA_MIN, PHA_MAX, and E_RANGE. E_RANGE specifies SPI energy range (0-low, PHA == 16384 to 32767; 1-high, PHA == 49152 to 65535). In physical units low range approximately corresponds to energies less then 2MeV, and high range – to the higher ones. The schematic representation of the SPI.-EBDS.-SET data structure can be found in Figure 15.

8.8 SPI Events Binning – *spihist*

spihist bins event data for individual detectors and/or for the entire detector array using the binning defined by *spibounds*. The events are grouped by pointing direction. Binned data can be produced in counts, counts/s/bin, or counts/s/keV. The available output FITS file formats are ISDC data structure or OGIP PHA-II formats. *spihist* creates event arrays, in the form of detector count spectra, according to various selection criteria and parameters.

Name	Type	Description
Input/Output		
in-og-dol	string	DOL of the input fits file which identifies the observation group to be processed.
det-spec-dol	string	Output FITS structure containing binned detector spectra and uncertainties. (e.g. "spi/evts_det_spec.fits(SPI.-OBS.-DSP.tpl)")
out-og-dol	string	DOL of the output observation group (e.g. "og_spi.fits[GROUPING]")
You can specify the output file		
outfile	string	The name of the output file with SPI events binning.
in case you want to run a script for specific scientific windows		
swg-index-dol	string	DOL of the input FITS file containing the index of science windows to be analyzed.
gti-dol	string	DOL of the input FITS file containing the list of good-time intervals for each detector and pointing.
deadtime-dol	string	DOL of the input FITS file containing the list of deadtime correction factors and livetimes for each detector and pointing.
ebounds-dol	string	DOL of the FITS table containing the energy bin boundaries (or raw pulse-height) as produced by *spihist*.
Parameters characterizing event binning		
dtype	integer	If the "PHA" *outputformat* option is selected, the binned data can be generated in units of counts (1), counts/s/bin (2), or counts/s/keV (3). You have to choose the desired format and enter the corresponding number. (e.g. 1).
psdtype	string	Determines which type of PSD selection is desired. There are 2 PSD flags, one in the raw data which is created by the on-board software, and one in the corrected (corr) data which is created on the ground. The user has the option of selecting "raw" or "corr". The value of the PSD flag, 0 or 1, indicates whether a PSD event is characterized by single or multiple peaks. (e.g. "raw")
detnums	string	Specifies the detectors for which binned data are produced. The detectors listed here should be a subset of the ones used in *spi_gti_creation*. To use a full set you should enter "-". This option is only available if the *outputformat* parameter is set to "PHA". (e.g. "-").

multipointing	string	This parameter let you to choose whether summed or distinct pointings are to be processed. To enter you selection you should type either "d" or "p". (e.g. "d").
tstart	string	The start of the spectra accumulation time interval. If the value is INDEF, tstart is taken from the pointing definition. (e.g. "indef")
tstop	string	The end of the spectra accumulation time interval. If the value is INDEF, tstop is taken from the pointing definition. (e.g. "indef")
outputformat	string	The available output file formats are "ISDC", in which case an ISDC table will be produced, or "PHA"in which case a PHA-II data structure will be at the output (e.g. "ISDC")

In the file **spi/evts_det_spec.fits** the data structure **SPI.-OBS-DSP** contains binned SPI events in the form of detector spectra. One row of this FITS table contains an event spectrum (column COUNTS and a column STAT_ERR for statistical errors) integrated for a particular detector and a given SPI pointing. The length of the vector column is equal to the number of energy bin considered. The lower and upper energy boundaries for each bin themselves are stored in the **SPI.-EBDS-SET** data structure produced by the *spibounds*.

The schematic representation of the SPI.-OBS.-DSP data structure can be found in Figure 15.

8.9 SPI Background Generation – *spiback*

spiback produces background models for imaging and spectral analysis. The simplest case is to assume a background that does not change with time. The background have then only one free parameter per detector in the image analysis. The goal of the background generation is to provide a model for the time (and energy) variations in order to limit the number of background parameters in a more realistic imaging solution. For example, one can assume that the background follows the time variation of the total number of Anti Coincidence Shield (ACS) counts, and then solve for 19 background scaling coefficients (one per detector) in the image reconstruction process.

spiback can output several background components, that can later be used independently in the imaging solution, which then solve for several sets of 19 coefficients. For example, one can combine one model following the IREM time variations with another following the ACS count rate variations.

The model background rates computed are averages over the corresponding period of good times. These rates are then multiplied by the livetime(s) to produce the final background counts stored in the output data structure.

The resulting background rates detector spectra are formatted as the events detector spectra.

Name	Type	Description
Input/Output		
in-og-dol	string	DOL of the input fits file which identifies the observation group to be processed.
out-og-dol	string	DOL of the output observation group (e.g."og_spi.fits[GROUPING]")

back-mod-idx	string	Name of output background index data file. (e.g. "spi/backgr_index.fits(SPI.-BMOD-DSP-IDX.tpl)")
back-mod-dol	string	Name of the output background model data file. This file will be in the same directory as the index data file. (e.g. "backgr_model.fits")
gti-dol	string	DOL of the input FITS file containing the list of good-time intervals for each detector and pointing.
deadtime-dol	string	DOL of the input FITS file containing the list of deadtime correction factors and livetimes for each detector and pointing.
ebounds-dol	string	DOL of the FITS table containing the energy bin boundaries (or raw pulse-height) as produced by *spihist*.
pointing-dol	string	DOL of the FITS table containing the observation pointing directions.
evts-det-spec-dol	string	DOL of the FITS table containing the detector event spectra
constant background model		
back-const	string	if you want a constant background component you should enter "YES", otherwise – "NO". (e.g. "YES")
back-const-value	real	if you want to have a constant background component you should specify the background level (cnts/det/sec/kev) (e.g. 1.e-5)
linear background model		
back-linear	string	if you want a linear background component you should enter "YES", otherwise – "NO". (e.g. "NO")
back-linear-mjd0	real	this parameter specifies the start time of the linear background component as Modified Julian Date
back-linear-slope	real	this parameter specifies the slope of the linear background component (cnts/sec/det/kev/day).
sinusoidal background model		
back-sincos	string	if you want a sinusoidal background component you should enter "YES", otherwise – "NO" (e.g. "NO") .
back-sincos-mjd0	real	this parameter specifies the phase of the SIN-COS background component as Modified Julian Date
back-sincos-period	real	this parameter specifies the period of the SIN-COS component (days)

back-sin-amp	real	this parameter specifies the amplitude of the SIN background component (cnts/det/sec/kev)
back-cos-amp	real	this parameter specifies the amplitude of the COS background component (cnts/det/sec/kev)
general background model		
back-model-gen	string	if you want a general background component you should enter "YES", otherwise – "NO". (e.g. "NO")
back-model-comp-1	string	for the general background model you should enter it's name or identifier.

The produced **SPI.-BMOD-DSP** in the file **spi/back_model.fits** contains model background rates (column COUNTS) for a particular detector and a given SPI pointing. The size of the vector column is equal to the number of energy bins considered.

The schematic representation of the SPI.-BMOD.-DSP data structure can be found in Figure 15.

Figure 15: Analysis Auxiliary Data and Intermediate-Level Data

8.10 Source Reconstruction and Spectra Extraction – *spiros*

The detailed description of *spiros* is given in the document written by its author P.H.Connell, University of Birmingham. Here we give a brief explanation of the program and describe only the most important parameters for a first try. Note that even for the explained parameters we don't give the full range of possible values.

The primary purpose of *spiros* is to use SPI data to locate **point** or **pointlike** sources in the observation field of view and to output a catalogue of their parameters along with images, their spectra and any flux variability in time.

spiros has three basic operating modes to choose from:

- **IMAGING** mode.
  Here the aim is only to locate point or pointlike sources in the observation field of view and to output a catalogue of their locations and width parameters. This step also produces images.
- **SPECTRAL** mode.
  In this mode *spiros* reconstructs spectra of sources in the SPI field of view. Source positions are either taken from the source-location process (IMAGING mode) or from a catalogue. The output spectra can be used for e.g.fitting in XSPEC spectral mode.
- **TIMING** mode.
  As in **SPECTRAL** mode a catalogue of known sources is used to create a light curve of sources and background in several energy bins (one flux value per pointing).

8.10.1 IMAGING mode.

Given its main task of locating point sources and creating images of them in the observation field of view the first question is how *spiros* goes about locating them.

A fast and simple method results by assuming some **prior knowledge** of the sources expected in the field of view, namely that they are **point** or **pointlike** and that there are only a **small finite** number of them, tens but not hundreds or thousands.

On this assumption the sources can be located using the **Iterative Removal of Sources** or **IROS** method which literally attempts to locate each source in the field of view one after the other from the strongest to the weakest.

This method works as follows:

- A fast but blurred **location image** is created which shows clearly the most probable location or region of the greatest source emission. This image may be called a "pixel independent correlation map" as it is constructed by scanning the imaging field of view with a "source probe" and calculating the flux by assuming all input counts are due to that source and any background events alone. This typically produces a "convolved" image with a global maximum at a good first guess for a probable source location.
- With this **approximate** location find the strength, probably too large, of the source and then the detector counts expected from it.
- Subtract source counts from the input count data to create **residue** count data more or less due to other sources not yet located.
- With these residue counts the procedure above is repeated creating a new location image, searching it for any new source and adding it to a growing list. Each time a new source is added to the list all sources are allowed to "float" to more precise locations before their counts are subtracted from the input counts.

IROS repeats the iterative procedure above, locating each new source approximately, always allowing them to float to more optimal locations, creating new residue count data and stopping when nothing significant can be found. This procedure can be repeated in any number of energy bins to calculate a mean location for each source over the entire spectrum range.

For the user running *spiros* in its **IMAGING** mode the main task is to get the appropriate binned count data output from *spihist*, decide the size of the field of view they wish to search and how many sources they wish to look for. The user may have an input catalogue of known sources to locate them again more precisely or find an extra one or two in addition or just to make an image of them.

The *spiros* parameters most important for the first try are the following:

Name	Type	Description
		Input/Output
mode	string	*spiros* operation mode - you can choose between "IMAGING", "SPECTRAL" and "TIMING" (e.g. "IMAGING")
in-og-dol	string	DOL of the input fits file which identifies the observation group to be processed.
out-og-dol	string	DOL of the output fits file. (e.g. "og_spi.fits[GROUPING]")
		Instrument and Background response
inst-resp-idx	string	DOL of the file which provides the count response in all detectors of SPI due to a point source anywhere in the instrument field of view and at any source photon energy. (e.g. "../IRF/SPI-IRF-index.fits[GROUPING]"
background-method	integer	Program *spiback* generates a first model of the background. Parameter **background-method** allows you following possibilities: **0** implies there is no background - only good for calibration sources; **1** implies the background values are given and will be subtracted from input counts first; **2** implies background rates in each detector are to be calculated independently; **3** implies background rates given in each detector are relative function values. (e.g. 3)
		Catalogue of known sources
source-cat-dol	string	DOL of the catalogue of known sources. In IMAGING mode this parameter is not obligatory but saves *spiros* from searching for sources whose location is more or less known.
location-max-error	real	If the input catalogue of known sources is specified then *spiros* compare the location errors of sources from catalogue with this parameter. If they are LESS than it the source will be flagged as having a **FIXED** location and width which will not be changed by *spiros*, otherwise they will be flagged as **VARIABLE** and their locations will be allowed to shift to a more optimum location when new sources are located. (e.g. 0.1)

Output catalogue and image files for IMAGING mode		
source-res	string	DOL of the output source catalogue with all known and any new located sources. (e.g. "spi/source_res.fits(SPI.-SRCL-RES.tpl)")
image-idx	string	Name of the output sky image index. (e.g. "spi/spiros_image_index.fits(SPI.-SKY.-IMA-IDX.tpl)"
image-inst	string	This parameter indicates if source flux intensity images are required for output. Possible values are "Y", "N" or the image name. If only "Y" is entered for the output dataset name will be made from the image index file name with "`\_intensity`" appended to it. (e.g. "Y")
image-err	string	This parameter indicates if source flux error maps are required for output. Possible values are "Y", "N" or the image name. If only 'Y' is entered for the output dataset name will be made from the image index file name with "`_error`" appended to it. (e.g. "Y")
image-sig	string	This parameter indicates if source flux sigma maps are required for output. Possible values are "Y", "N" or the image name. If only 'Y' is entered for the output dataset name will be made from the image index file name with "`_sigma`" appended to it. (e.g. "Y")
iteration-output	string	This parameter indicates that in the search procedure which locates sources one by one from the strongest to the weakest there will be output of images at each search iteration showing the sources known or located and the emission residue remaining. It is the residue image that SPIROS will search to see if there are any new sources to be found. Possible values are "Y" and "N". (e.g. "Y")
Output image array parameters for IMAGING mode		
reference-coord	string	Output image reference coordinate system. This parameter will normally have the value of "RADEC" but if "GALACTIC" is specified the observation pointing directions and imaging frame of reference will be translated into (l, b) galactic coordinates. (e.g. "RADEC")
image-fov	string	Extent and location of output image. "POINTING+FCFOV" will set the centrepoint of the image array to that of the observation field of view. The size of the image field of view is extended by the FULLY CODED field of view of SPI, about $\pm 8^o$. (e.g."POINTING+FCFOV")
blur-size	real	FWHM blurring for display of point sources. It should be not too small or you may not immediate "see" point sources in the image (e.g. 0.5)

Image-proj	real	Output image projection type. Possible values are “CAR”, “TAN” and “AIT” (e.g. “CAR”)
Source location parameters		
nofsources	integer	The maximum number of point sources *spiros* will search for unless a new source falls below the sigma threshold given by parameter **sigmathres** in which case it will stop searching. (e.g. 1)
sigmathres	real	The sigma threshold to reject new sources located and stop searching for anymore. (e.g.3.0)
kofsources	string	Shape of sources to be searched for. "POINT" prompts a search for as many point sources as given by parameter **nofsources**. (e.g. "POINT")
srclocbins	string	With this parameter the user can try a one-step approach by binning count data only once in the large number of energy bins required for spectra then using this parameter to select a smaller subset of bins for source location. "ALL"will locate sources in **each** energy bin of the input count spectrum and form a "sigma weighted" mean value to output in the result images; "SUM" will locate sources in **one** energy bin covering the input energy spectrum. (e.g. "SUM")
Control of source flux, location and width optimization		
optistat	string	For the count values expected from SPI exposures the noise or statistics in them can generally be expected to be **Gaussian** requiring the minimization of a $\chi^{\mathbf{2}}$ statistic. In some cases, especially of weak diffuse emission, the count noise can be expected to be **Poisson** requiring the minimization of a Maximum Likelihood parameter such as the **Cash** statistic. The possible values of the parameter are "CHI2", "LIKEH". (e.g. "CHI2")
maxlikprec	real	This is the stopping criteria in optimizing a χ^2 or **ML** statistic and is used in conjunction with the source location precision **srclocprec** or width precision **srcwidprec** to stop improving source location or width values. (e.g. 0.2)
srclocprec	real	In searching for sources SPIROS is always allowing them to simultaneously "float" to more accurate locations and this parameter is the location precision stopping criteria. In iteratively finding better locations SPIROS finds the **largest** change the location of any source. If it falls within the value of **srclocprec** and the change in the ML parameter within **maxlikprec** then the current source locations are returned as optimal. (e.g 0.01)

srcwidprec	real	In searching for **POINTLIKE** sources SPIROS also allows their widths to vary. If the largest change in any source width falls within **srcwidprec** and the change in the ML parameter within **maxlikprec** then the current source widths are returned as optimal. (e.g. 0.1)
solution-constr	string	Here the user can tell SPIROS to solve its imaging equations linearly ("NONE") or with a positivity constraint ("POSITIVE"). (e.g. "NONE").
chilocstep	real	Source location sampling step [degrees]. (e.g. 0.1)
chiwidstep	real	Source width sampling step [degrees]. (e.g. 0.5)

The results produced by *spiros* are written into the directory **spi**. After running program in IMAGING mode with **nofsorces**=m you will find the following files (if you don't modify the names in the parameter file):

```
spiros_image_index.fits
```

This file contains an index for all image data structures **SPI.-SKY.-IMA** generated by *spiros*. In this file you can find the information about the energy range for each image, the exposure time, and the number of iterations used by *spiros*.

```
spiros_image_index_intensity_1.fits
spiros_image_index_intensity_2.fits
             ...
spiros_image_index_intensity_(m+1).fits
```

These files contain the intensity map of the desired sky refion after the iterative removing of 0,1...m sources.

```
spiros_image_index_error_1.fits
spiros_image_index_error_2.fits
             ...
spiros_image_index_error_(m+1).fits
```

contain corresponding error maps.

The iterative significance maps are written to

```
spiros_image_index_sigma_1.fits
spiros_image_index_sigma_2.fits
             ...
spiros_image_index_sigma_(m+1).fits
```

and the resulted significance map

```
spiros_image_index_sigma_result.fits
```

The *spiros* catalogue of found/known sources can be found in

`source_res.fits`

This file contains data structure **SPI.-SRCL-RES** with the following columns:

Column name	Description
SOURCE_ID	ISDC unique source identifier
DAY_ID	Modified Julian Date of source's first identification
NAME	One commonly used name for the source
CLASS	source classification code
RA_OBJ	Source right ascension in degrees
DEC_OBJ	Source declination in degrees
ERR_RAD	Error radius
RELDIST	Relative distance of the source (= d/(r1+r2)) where d = distance to catalog source identified with the source and rn are the respective error radii of the sources.
SPA_MODL	Model for source spatial extension (point, disk, ellipse, square, gaussian, Bspline, etc..)
SPA_NPAR	Number of parameters for source spatial extension
SPA_PARS	Parameters for source spatial extension
SPE_MODL	Model for source spectrum (XSPEC syntax)
SPE_NPAR	Number of parameters for source spectrum
SPE_PARS	Parameters for source spectrum
VAR_MODL	Model for source intensity variability (const, sin, burst)
VAR_NPAR	Number of parameters for source intensity variability
VAR_PARS	Parameters for source intensity variability
COMMENTS	Comments
SPI_FLUX_1	SPI flux in the soft SPI energy band (<2MeV), according to input catalogue
SPI_FLUX_2	SPI flux in the hard SPI energy band(>2MeV), according to input catalogue
ISGR_FLUX_1	ISGRI flux in the soft ISGRI energy band, according to input catalogue
ISGR_FLUX_2	ISGRI flux in the hard ISGRI energy band, according to input catalogue
PICS_FLUX_1	PICsIT flux in the soft PICsIT energy band, according to input catalogue
PICS_FLUX_2	PICsIT flux in the hard PICsIT energy band, according to input catalogue
JEMX_FLUX_1	JEMX flux in the soft JEMX energy band, according to input catalogue
JEMX_FLUX_2	JEMX flux in the hard JEMX energy ban, according to input catalogued
E_MIN	Lower energy boundaries (vector column with the length equal to the number of energy bins defined in *spibounds*)
E_MAX	Upper energy boundaries (vector column with the length equal to the number of energy bins defined in *spibounds*)
FLUX	Flux values(vector column with the length equal to the number of energy bins defined in *spibounds*)
FLUX_ERR	Flux errors(vector column with the length equal to the number of energy bins defined in *spibounds*)
SEL_FLAG	Source selection flag (0 in case of no problems, 1 in case of the problems).

The spectrum information is upgraded in this file after running *spiros* in **SPECTRAL** mode. The additional files that appear after this run in the directory **spi/** are

`source\_spec\_index.fits`

with an index and output observation group;

`source\_spec\_index\_data.fits`

with the spectrum of each source found. For each source the data structure **SPI.-SRC.-SPE** is filled. The meaning of the columns in the fits table is described in the next Table:

Column name	Description
CHANNEL	Channel numbers for the countrates
RATE	Countrates in the defined channels
STAT_ERR	Statistical uncertainty of the countrates
SYS_ERR	Systematical uncertainty of the countrates
QUALITY	Quality flags for the channels
GROUPING	Grouping flags for the channels

After running *spiros* in **TIMING** mode the following files will be added to the **spi** directory:

`source\_timing\_index.fits`
`source\_timing\_index\_data.fits`

The first one is the index file and the second one contains the light curve for all sources found. The data structure **SPI.-SRC.-LCR** have the following columns:

Column name	Description
PTID_SPI	ID of the SPI pointing defined for this flux value
OB_TIME	OBT at the middle of the SPI pointing
TIME	Time at the middle of the SPI pointing (in ISDC-JD)
E_MIN	Minimum energy of the energy bin
E_MAX	Maximum energy of the energy bin
E_MEAN	Mean energy of the energy bin
FLUX	Flux of the source
STAT_ERR	Statistical error of the flux
SYS_ERR	Systematic error of the flux
QUALITY	Quality flags for the energy bins

8.11 Image Reconstruction – *spiskymax*

The detailed description of *spiskymax* is given in the document written by its author A.Strong, MPE Garching.

The aim of *spiskymax* is to generate images from SPI data. SPI is a coded-mask instrument, so direct deconvolution is in principle possible, but in practice the response is complex and the data include many pointing directions of the instrument, so 'indirect imaging' is essential. Indirect imaging implies 'forward-folding': for any candidate image we convolve with the instrument response function and compare the result with the observed data. This gives the basis for any iterative method which seeks to successively improve the agreement of the predicted with the observed data by adjusting the image. One approach is to regard the image as made up of 'point sources' and to adjust their positions and fluxes to give a best-fit to the data. This is the basic principle of the *spiros* method.

spiskymax on the other hand regards the image as a pixelated skymap, and the aim is to obtain the intensity in each pixel. The most important idea is that the data constrain the image within some limits in an N-dimensional space, where N is the number of pixels. Hence there is no unique 'best' image and we have to make some choice out of all the possible images within the constrained region. Maximum Entropy method as implemented here is one way of doing this, and of quantifying the uncertainty of the result. Since the number of pixels is usually large (e.g. 10^4-10^6) the techniques involved are rather different from those of model-fitting.

spiskymax is adapted to the particular needs of SPI. The background temporal variations are treated via a template prepared by *spiback*, and the coefficients are fitted during the imaging process. The input count spectra contain data for many energy bins, and *spiskymax* analyses a subset (or all) of these energies as specified by the parameters *energy_range_min, energy_range_max*. The number of iterations can be specified since the automatic stopping criterion is not always appropriate and in any case may not be reached in the CPU time available. Sources to be analyzed are defined by their positions in the input source catalogue (SPI.-SRCL-CAT); only those with the SEL_FLAG flag =1 are analyzed, and their fluxes and 1σ errors written to the output catalogue.

After the image is produced, the flux and its error for a number of user-defined sources can be optionally determined. Each source is specified in terms of a position and 'ON' and 'OFF' radii. The ON region is the circle centered on the source position with radius ON and the OFF region is the annulus between the ON and OFF radii. The source flux is defined as

Σ(intensity in ON region)/Σ(intensity in OFF region) *solid angle(ON)/solid angle(OFF).

The error is based on a Bayesian analysis which marginalizes over all the unwanted degrees of freedom, so the significance of a source by this method may not correspond to a 'classical' significance level. In general significances increase for smaller skymaps since the degrees of freedom decrease.

The *spiskymax* parameters most important for the first try are the following:

Name	Type	Description
		Input/Output
rogroup	string	DOL of the input fits file which identifies the observation group to be processed.
rwgroup	string	DOL of the output fits file. (e.g. "og_spi.fits[GROUPING]")
irf_input_file	string	DOL of the IRF index file with SPI response information (e.g. "../../ic/spi/rsp/spi_irf_grp_0007.fits[GROUPING]")
source-cat-dol	string	DOL of the input catalogue (e.g. "source-cat-in.fits[1]")

Output image definition		
image-idx	string	DOL of the output skymap index file. (e.g. "spi/skymax_index.fits(SPI.-SKY.-IMA-IDX.tpl)"
image-int	string	Name of the output skymap images file. (e.g. "skymax_image.fits").
source-res-dol	string	DOL of the output source catalogue with flux spectra and error bars. (e.g. "spi/spiskymax_sources.fits(SPI.-SRCL-RES.tpl)")
energy_range_min	integer	minimum energy range sequence number as in ebounds file: 1,2,3... energy ranges energy_range_min to energy_range_max are processed. (e.g. 1)
energy_range_max	integer	maximum energy range sequence number. (e.g. 1)
skymap_system	string	Input skymap coordinate system C=celestial, G=Galactic. (e.g. "C")
image-fov	string	Choice of how the image field of view is defined. Must be one of: "SURVEY"; "USER"; "POINTING"; "POINTING+FCFOV"; "POINTING+ZCFOV"; "POINTING-CENTER". The choice of "POINTING+FCFOV" will set the centrepoint of the image array to that of the observation field of view. The size of the image field of view is extended by the **FULLY CODED** field of view of SPI, about $\pm 8^o$. (e.g. "POINTING+FCFOV").
max_iter	integer	maximum number of iterations (e.g. 50)
image_default	real	image default intensity, cm^{-2} sr^{-1} s^{-1}. The value to be assigned to pixels which are unconstrained by the data. Set to the expected average intensity. This parameter can be adjusted to optimize the maps but the result should not be too sensitive to its value. (e.g. 1.e-3)
Source flux definition.		
source_ON_radius_1	real	ON radius (degrees). (e.g. 2.0)
source_OFF_radius_1	real	OFF radius (degrees). (e.g. 5.0)

If you follow the naming scheme used in the provided parameter files then in the directory **spi** you find the following files after the run of *spiskymax*

```
skymax_index.fits
skymax_image.fits
```

```
spiskymax_sources.fits
```

The first file **skymax_index.fits** is an index file. File **skymax_image.fits** contains the image produced by *spiskymax*. File **spiskymax_sources.fits** is a copy of the input catalog.

9 Cookbook

Now we will see how to analyze your data using the script combining all the executables described above. Make sure to use a sufficient machine (e.g. isdcul10, isdcul19, crab, etc. at ISDC)

9.1 Preparation

During the software installation the environment is settled automatically. At ISDC you should do it manually (to make sure you have the latest software version). At the moment there are two possibilities of setting the environment. The first one is general for all the 4 instruments but is not fully tested yet. So if you have problems with it send an e-mail to Bruce (bruce.oneel@obs.unige.ch). Thus you will help us to make it working properly. In any case the second variant should work for sure. So type either

```
source /isdc/scripts/login --ISDC_ENV=/isdc/integration/osa_int/current
 --ROOTSYS=/isdc_soft_platform/root
```

or

```
source /isdc/scripts/login --ISDC_ENV=/isdc/integration/spi_int/sw_rep
 --ROOTSYS=/isdc_soft_platform/root
```

Before starting the analysis in your home directory you should create a directory **pfiles/** with the parameter files. To do this give the following commands (they are different in case you don't work at the ISDC):

```
cd
mkdir pfiles
cp /home/isdc_guest/spi_int/pfiles/*.par ~/pfiles  (if you work at ISDC)
or
cp $ISDC_ENV/pfiles/*.par ~/pfiles                 (in any other environment)
```

Now you should create the directory **data_rep/** and the directory **obs/**:

```
cd
mkdir data_rep
cd data_rep
mkdir obs
```

To set the links to the reference orbit test data at ISDC give the following commands:

```
ln -s /isdc/testdata/e2e_e/data/cons/ops_1/scw scw
ln -s /isdc/testdata/e2e_e/data/cons/ops_1/ic  ic
ln -s /isdc/testdata/e2e_e/data/cons/ops_1/idx idx
ln -s /isdc/testdata/e2e_e/data/cons/ops_1/aux aux
```

To use other local data sets do similar linking, e.g.

```
ln -s /here/are/the/prepared/data/scw scw
```

and similar for **ic, idx, aux**

In the **scw/** directory you can easily see, which revolution numbers are available:

```
ls scw/
```

Now you have to create an observation group. To do this you should specify science windows you want to analyze. Open with an editor an ASCII file **dols.txt** (e.g. emacs dols.txt) and type in the following:

```
scw/0087/008700010010.000/swg_prp.fits[1]
scw/0087/008700020010.000/swg_prp.fits[1]
scw/0087/008700070010.000/swg_prp.fits[1]
scw/0087/008700080010.000/swg_prp.fits[1]
```

To create an observation group with the name **obs_id** give the following command:

```
og_create idxSwg="dols.txt" ogid="obs_id" baseDir="." instrument="SPI"
```

This command also creates a new directory **obs/obs_id** where the following analysis will take place.

Go to your new obs branch:

```
cd obs/obs_id
```

Now you are ready to start the scientific analysis of your data.

9.2 Example 1: image of the 511 keV line reference orbit test source

To run the script type:

```
spi_osa
```

After the launch of the GUI you will see the following picture:

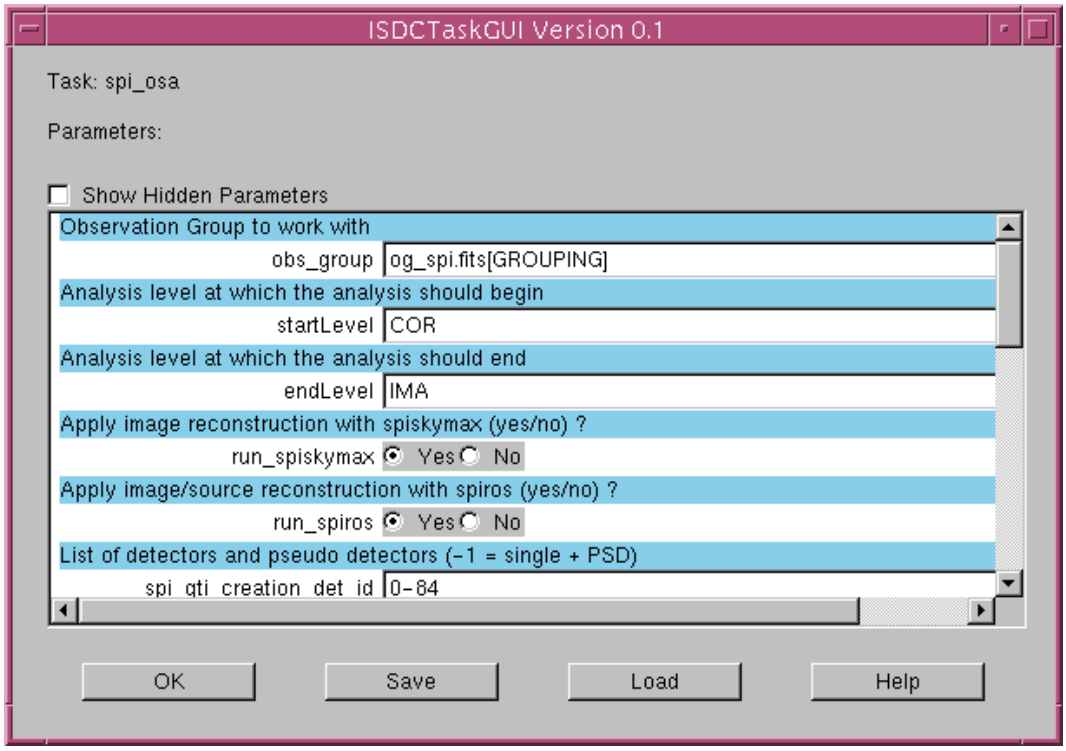


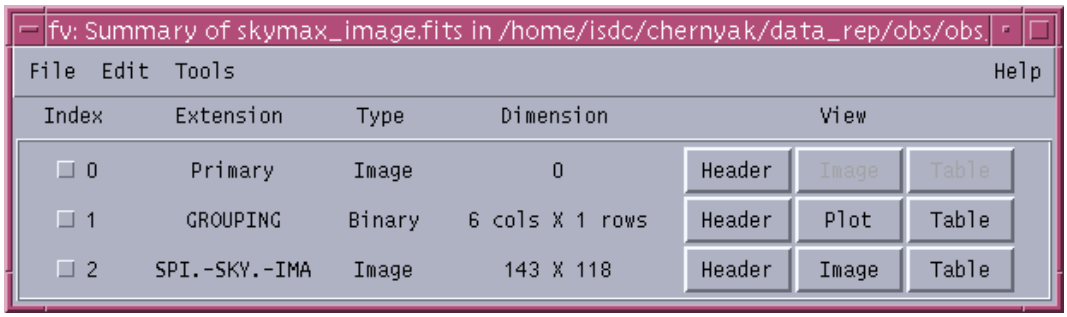
Figure 16: screenshot of the *spi_osa* script GUI

Blue lines described the parameters you have to enter. To see the hidden parameters mark the box "Show hidden parameters". For this example enter the following values:

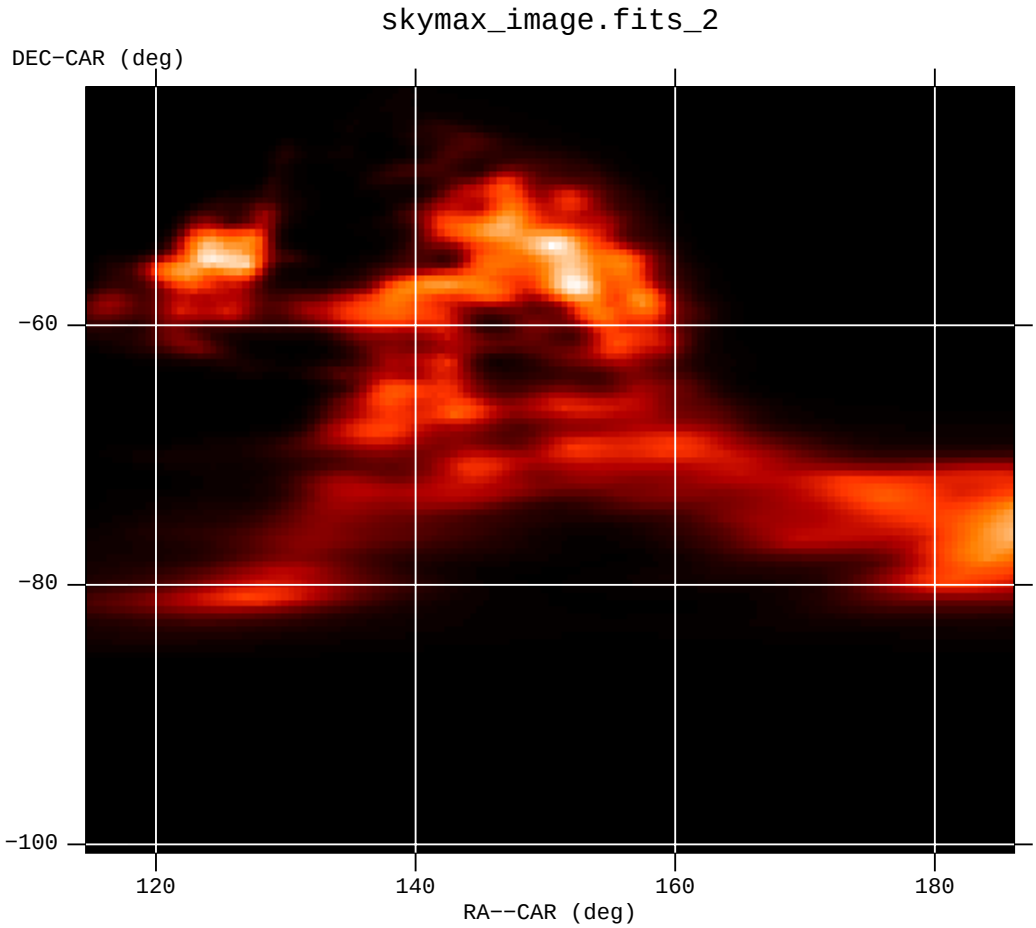
Name	Value
Specific Script Parameters. For levels definition see e.g. section 6	
startLevel	COR
endLevel	IMA
run_spiskymax	YES
run_spiros	YES
Parameters for *spi_gti_creation*	
spi_allgti_det_id	0-84

Parameters for *spibounds*	
spibounds_nregions	1
spibounds_regions	500,520
spibounds_nbins	1
Parameters for *spiros*	
spiros_image-fov	POINTING+FCFOV
spiros_mode	IMAGING
Parameters for *spiskymax*	
spiskymax_image-fov	POINTING+FCFOV
spiskymax_energy_range_min	1
spiskymax_energy_range_max	1

The results produced by the script can be found in the directory **spi/**. The main interest represent files **spiros_image_index_sigma_result.fits** with the significance map build by *spiros* and skymax_image.fits with the intensity map build by *spiskymax*. The easiest way to look to this images is to type `fv` and the name of the file (e.g. `fv skymax_image.fits`. Then the following table appears:



Press button **Image** and you will see the resulted intensity map (you can modify the color scheme using "colors" menu):


skymax_image.fits_2
DEC−CAR (deg)
−60
−80
−100
120
140
160
180
RA−−CAR (deg)

10 Known Limitations

TBW

References

[1] ISDC/INTROIDA Introduction to the INTEGRAL Data Analysis.